

UC Irvine

UC Irvine Previously Published Works

Title

Spatially-resolved measurements of soot size and population in a swirl-stabilized combustor

Permalink

<https://escholarship.org/uc/item/9k12q39q>

Journal

Symposium (International) on Combustion, 20(1)

ISSN

0082-0784

Authors

Wood, CP
Smith, RA
Samuelsen, GS

Publication Date

1985

DOI

10.1016/s0082-0784(85)80598-1

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at

<https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

SPATIALLY-RESOLVED MEASUREMENTS OF SOOT SIZE AND POPULATION IN A SWIRL-STABILIZED COMBUSTOR

C. P. WOOD

Staff Research Associate

R. A. SMITH

Research Assistant

G. S. SAMUELSEN

Professor of Mechanical Engineering

UCI Combustion Laboratory

Mechanical Engineering

University of California

Irvine, California 92717

Isooctane, and mixtures of isooctane with various ring and aromatic compounds blended to yield the same smoke point were separately injected through a twin-fluid atomizer into a turbulent, swirl-stabilized model combustor. A nonintrusive optical probe based on large angle (60° , 20°) intensity ratio scattering was used to yield a point measurement of soot particulate in the size range of 0.08 to 0.38 μm . The velocity and temperature fields were characterized by a two-color laser anemometer and thermocouple, respectively. Sooting was low or nonexistent in regions of high temperature and relatively high in regions of depressed temperature. The addition of ring compounds to isooctane increased the amount of soot produced and changed the location of peak soot production. The total amount of soot produced depended on fuel type for those fuels of equivalent smoke point, with the double ring compounds yielding significantly more soot than the single ring blend. The amount of soot produced was reduced by a reduction in fuel loading. Scanning electron micrographs of extracted samples established that the optical technique resolved the large particle wing of the soot size distribution. The results point to the complexity of soot production in flows dominated by strong aerodynamics, and the importance of nonintrusive optical measurements to both unravel the processes of formation and burnout and provide the information necessary to guide combustor and nozzle design.

Introduction

Soot production in practical, continuous combustion systems such as gas turbines, boilers, and furnaces depends on the aerodynamic field and fuel distribution in addition to the thermal and chemical environment. The production of soot in such systems is likely to increase with the transition to fuels derived from lower quality or non-petroleum stock, or refined to a lesser extent in order to extend utilization of the base stock. Accompanying this deterioration of fuel quality is an increased propensity to produce soot. Hence, an understanding of soot production in turbulent, recirculating (i.e., complex) flows is desirable as a guide by which the aerodynamic field and fuel distribution, for example, can be tailored to minimize soot formation and maximize soot burnout.

Toward this end, spatially resolved measure-

ments of soot within the combustor are needed. Extractive probes have been used in the past to derive this set of information (e.g., [1, 2, and 3]) but, in complex flows where backmixing can exacerbate and widely distribute perturbations introduced by the presence of a physical probe, caution must be exercised in the use of such methods.⁴ This may include limiting the measurements to the combustor exit-plane, far downstream of the recirculation zone. Such a limit substantially restricts the information available. Excluded is the spatial distribution of local soot size and soot population in the near wake of the recirculation zone and within the recirculation zone itself. Measurements in such regions must be nonintrusive and, therefore, rely on optical techniques.

Optical techniques have been successfully employed to measure soot in relatively simple flows (e.g., premixed and diffusion flames^{5,6,7}), but ap-

plications to complex flows are limited. Intensity ratioing has been used, for example, to measure soot particulate in model complex flow combustors for gaseous propylene,⁴ prevaporized liquid fuels,⁸ and spray atomized liquid fuels.⁹ These studies have established the potential for optical measurements of soot in complex flows and, in one case, assessed the perturbation of an extractive probe.⁴ However, the interpretive value of the data are limited in the absence of an aerodynamic and thermal characterization of the flow field. The present study provides this information. Radial profiles of soot size and population were obtained at three axial locations for spray-atomized liquid isooctane and three isooctane blends mixed to yield the same ASTM smoke point. Streamlines and isotherms were constructed from velocity and temperature measurements made at six axial locations for one of the isooctane blends.

Experiment

Combustor

The combustor, presented in Fig. 1, features an aerodynamically controlled, swirl-stabilized recirculation zone.^{9,10} The housing consists of an 80 mm I.D. cylindrical stainless steel tube that extends 32 cm from the plane of the nozzle. Rectangular, flat windows (25×306 mm) are mounted perpendicular to the horizontal plane on both sides of the combustor tube to provide a clear, optical access for the laser measurements.

A set of swirl vanes (57 mm O.D.) are concentrically located within the tube around a 19 mm O.D. centrally positioned fuel delivery tube. Dilution and swirl air are metered separately. The dilution air is introduced through flow straighteners in the outer annulus. The swirl air passes through swirl vanes with one hundred percent (100%) blockage which imparts an angle of turn to the flow of 60° . For the swirl-to-dilution air flow ratio of 1.66 used in the present study, the swirl number obtained by integrating across the swirl vanes is 1.3; that obtained by integrating the total inlet mass flux is 0.5. Prototype 60° swirl vanes with a seventy percent (70%) blockage, used for prevaporized fuel injection,⁸ were

not adequate for the liquid injection. Higher blockage provides a wider range of stable operation for the liquid injected fuels.

Fuel was introduced through a twin-fluid injector designed for the present study by Parker-Hannifin. Sauter Mean Diameter (SMD) was measured using a Malvern ST2200 laser diffraction instrument as a function of nozzle air-to-fuel mass ratio (Fig. 2).¹¹ Although the values of SMD approach the limit of resolution for the Malvern as nozzle air-to-fuel ratio is increased, the trend toward enhanced atomization quality is clearly evident. The results of the present work were obtained for an air-to-fuel mass ratio of 3.0.

Fuels

Four liquid fuels of varying molecular structure representative of compounds found in petroleum, shale, and coal derived fuels were used in this study. Isooctane (2,2,4-trimethylpentane) and three blends consisting of mixtures of isooctane with one of three compounds with varying degrees of saturation and ring number—toluene, tetralin (1,2,3,4-tetrahydronaphthalene), or 1-methylnaphthalene—were used. The isooctane/tetralin blend served as the base fuel.

The amount of hydrocarbon blended with the isooctane was selected to yield the same ASTM smoke point (23 mm) as that obtained for a typical JP-8 jet fuel stock.³ Table I summarizes the composition and the actual smoke point found for each blend. The smoke points, while not identical, are equivalent within the achievable accuracy of the smoke point test (± 1 mm).

Soot

Intensity ratioing was adopted for the point-measurement of particle size and population of soot particulate.⁴ Laser lines from a 5-watt Model 165 Spectra-Physics argon-ion laser (Fig. 3) were separated by a dispersion prism to resolve the blue line (488.0 nm). The beam was focused to a $110 \mu\text{m}$ waist using a 50 mm diameter $f/5$ focusing lens. The scattered intensity was detected at 60° and 20° which provided a particle size detection band of 0.08

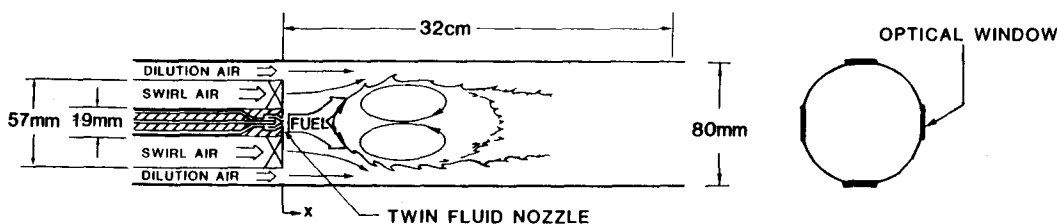


FIG. 1. Dilute swirl combustor.¹⁰

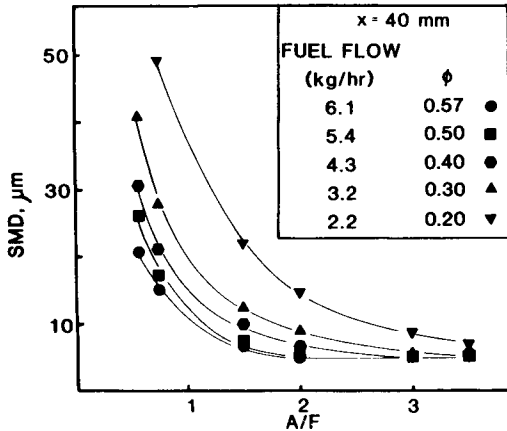


FIG. 2. Nozzle performance. Malvern ST2200 measurements of SMD in an isoctane/tetralin blended liquid spray from an air-assist nozzle.¹¹

$\mu\text{m} < d < 0.38 \mu\text{m}$. Other angles were available but $60^\circ/20^\circ$ provided the smallest resolvable size ($0.08 \mu\text{m}$) of those pairs available.

The scattered light was focused to two photomultiplier tubes (RCA Model 8575) having quantum efficiencies of approximately 15% at the 488.0 nm wavelength with pinhole aperture diameters of 200 μm . The supply voltage to the tubes was approximately 1200 volts.

The output signals from the photomultiplier tubes were passed into a Spectron Development Laboratories (SDL) Model LA-1000 logarithmic amplifier which converted the negative current to a positive voltage and was scaled for +10 volts peak output when the input current was -1 mA . The amplified signals were then processed by an analog subtractor circuit in an Intensity Ratio Processor (SDL Model

TABLE I
Fuel summary

Fuel ^a	Smoke point ^b	H wt. %
Isooctane	43.0	15.79
Blend 1		
21% toluene/79% isooctane	24.0	14.02
Blend 2		
8% tetralin/92% isooctane	25.3	15.06
Blend 3		
5% 1-methylnaphthalene/ 95% isooctane	22.2	15.16

^aBlend composition stated in volume percent.

^bDistance above base of burner in mm at which sooting first occurs.

Source: Reference 3.

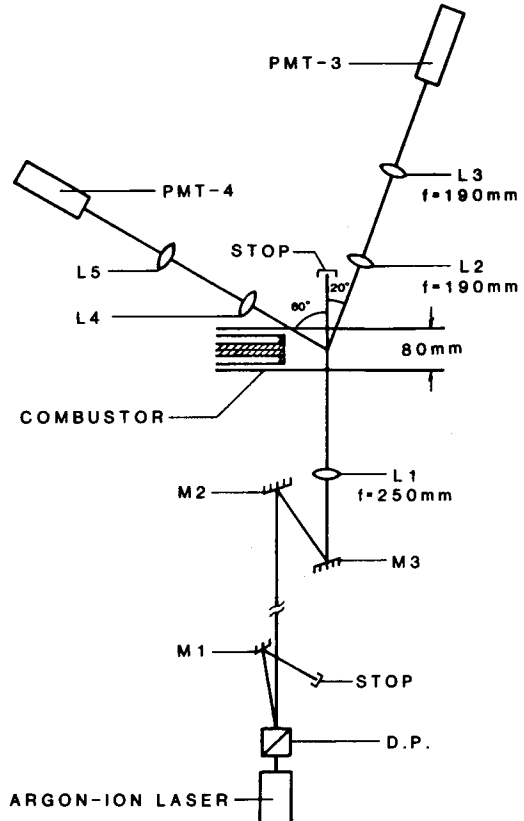


FIG. 3. Soot measurement instrument. Based on Mie scattering collected at two angles, 60° and 20° .

RP-1001) which amplified the signals with a gain of five and converted the signals to 8-bit binary numbers.

The binary output was fed to a microcomputer, which resolved this output into 62 bins. The size distribution was determined by the number of counts in each bin, where each bin encompassed a discrete size range. The counts in each bin were then divided by the collection time, resulting in a count rate (counts/sec). A histogram was then generated of normalized data rate versus size (in microns). The normalization of this histogram was under the operator's control through the system software. The histogram could be normalized to itself (giving the bin with the highest sooting rate a normalized rate of 1.0); it could be normalized to the highest sooting rate among all the histograms generated for a particular fuel; or it could be normalized to the highest sooting rate among any number of fuels or operating conditions. The results of this normalization procedure are evident in Fig. 6 and Fig. 7.

The interpretation of the measured intensity ratio is based on the analysis of the Mie scattering properties of a homogeneous, isotropic spherical

particle. Soot, a nonspherical scatterer with an index of refraction of some uncertainty, therefore requires special consideration. An evaluation of such effects, considered in an earlier study, concluded that the combined error was 20–30 percent with some broadening of the distribution.⁴

The optically-measured data rate is reduced on the small particle side of the peak due to the Gaussian intensity profile of the incident laser beam. A relatively small particle passing through the laser beam at the wing of the Gaussian intensity profile may not scatter enough light to meet established threshold levels on the Intensity Ratio Processor, whereas a larger particle, passing through the same region of the beam, will scatter enough light to be recorded. This acts to artificially suppress the low end of the distribution. This inaccuracy is amenable to an analytically derived "probe-volume" correction which has been implemented through the reduction software, in essence giving the system a flat response throughout the range of sizes it is theoretically capable of measuring.

Use of intensity ratioing in highly turbulent, non-uniform flowfields presents an additional problem associated with steering of both the incident beam and the scattered light. This was mitigated in the present experiment by use of a relatively small duct diameter and by acquiring the majority of data in the half plane closest to the receiving optics. Checks on accuracy were conducted by using various sizes, under cold flow conditions, of monodispersed polystyrene latex particles and, under hot flow conditions, comparing scanning electron micrographs of extracted samples to optical measurements of soot size at the probe inlet. An intensity validation technique is under development to provide a direct measure and to monitor in real-time the effect of beam steering. Other sources of inaccuracy, as well as repeatability, are discussed elsewhere.^{8,9}

Velocity

Velocity measurements were made using a two-color laser anemometry (LA) system based on a 200 mW argon-ion laser (LEXEL Model 75). A set of perpendicular interference fringes, spaced at 2.6 μm for the green beams and 2.5 μm for the blue beams, were oriented at a common point within the combustor to yield the axial and azimuthal velocity components, respectively. A 40 MHz frequency shift (TSI Model 915 Bragg Cell) was applied to each pair of beams to eliminate directional ambiguity that otherwise results from the turbulent, recirculating flow. The receiving optics were placed at an angle of 20° off direct forward scatter which resulted in a probe volume of 0.022 mm³ and a cross-sectional area perpendicular to the axis of measurement of 0.10 mm². The flow was seeded with 1 μm alumina particles using a liquid suspension atomization technique.¹²

Streamlines were calculated from velocity and temperature measurements at ten radial locations at each of six axial stations. Velocity data were biased in the recirculation region by the spray atomized fuel droplets and, as a result, the streamline structure in the recirculation zone was established using the temperature data and velocity data obtained from gaseous propane injection, as well as the current velocity set.

Temperature

The temperature probe consisted of a platinum-13% rhodium vs. platinum exposed junction thermocouple. The thermocouple was supported by a 1.6 mm (0.063-inch) O.D. inconel tube, 51 mm (2-inches) in length, which in turn was mounted to a 6.4 mm (0.25-inch) O.D. inconel support to provide structural rigidity. Water cooling was provided in the larger inconel tubing to assure the structural integrity of a necessary probe bend, but only to within 42 cm (16.5-inches) of the thermocouple so as to minimize conduction losses down the length

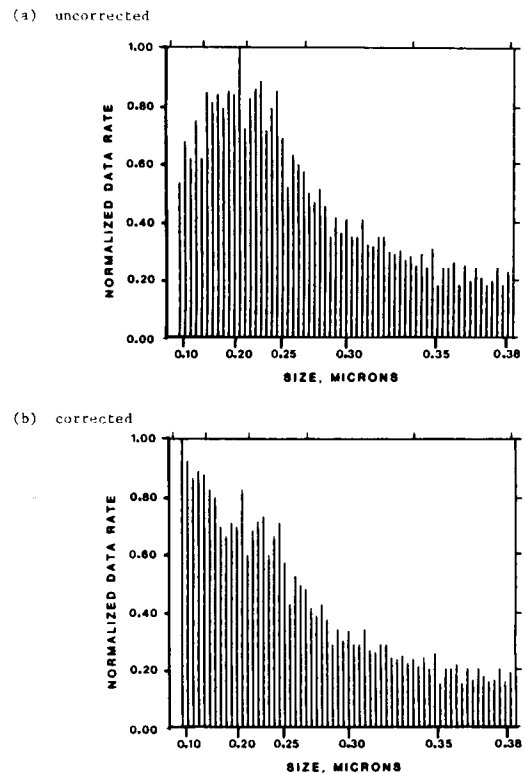


FIG. 4. Representative optical soot data. Histogram of normalized data rate versus soot size at one location in the combustor (isooctane/tetralin $\phi = 0.5$, $r/R = 0.83$, $x/R = 5.0$): (a) Uncorrected; (b) corrected.

of the probe. The probe was mounted on a three-axis positioning traverse consisting of three orthogonally oriented screw motion assemblies. With this system, the thermocouple junction could be placed within an accuracy of ± 0.07 mm (± 0.003 -inch). The temperature was displayed on a digital thermometer (Fluke Model 2160A) having an analog output of 1.0 mV per °F. The effects of probe perturbation on the mean values and statistics of the local aerodynamic field have been evaluated in the present combustor for a thermocouple probe of similar design.¹³ The variation in the mean values range from zero to a few percent, except on the centerline and in the recirculation zone where the variation approaches twenty percent. The inference is that the mean temperature data presented here are affected by probe perturbation to a similar extent. Parenthetically, the statistical properties (e.g., u' , w' , $u'w'$), not considered in the present study, are more sensitive to probe perturbation. The data presented are uncorrected for radiation loss.

Test Conditions

Tests were conducted at overall equivalence ratios of 0.3 and 0.5. Although not optimum for each individual case, an air-to-fuel ratio of 3.0 was selected as the operating condition which provided the most satisfactory performance (highest stability) for the group of fuels tested. The nozzle air was in

addition to the main air (swirl plus dilution) and corresponded to ten and six percent of the main air at $\phi = 0.5$ and $\phi = 0.3$, respectively. The combustor was operated at a reference velocity of 7.5 m/s and atmospheric pressure to provide for the necessary optical access and ease of operation with the relatively complex and unhardened optical system employed. The effect of pressure, an important parameter in the production of soot, is appropriate for evaluation once the utility and applicability of the optical system is established and adaptability of elevated pressure systems to optical access is demonstrated.

Results

Validation

An example of the uncorrected and "probe-volume" corrected data provided by the optical system is shown in Fig. 4 for the base fuel (isooctane/tetralin blend) at $\phi = 0.5$. The histogram represents the distribution of intensity ratio for 30131 validated samples. The total data rate for this case (2643 Hz) is the number of validated samples (30131) divided by the total sample time (11.4 seconds) and represents the sum of the bin data rates for each of the 62 bins comprising the histogram. The total data rate for each sampling location for this case

TABLE II
Data rate (Hz)

Fuel	Equivalence ratio ^a ϕ	Axial x/R	Location						Figure
			Radial r/R						
			0	0.17	0.33	0.50	0.67	0.83	
Isooctane	0.5	1.6	57	70	66	61	109	247	7a
		3.0	0	0	0	0	7	26	
		5.0	0	0	0	0	0	1	
Blend 1 21% toluene/ 79% isooctane	0.5	1.6	30	72	122	204	406	581	7b
		3.0	0	0	1	6	65	296	
		5.0	0	0	0	4	59	419	
Blend 2 8% tetralin/ 92% isooctane (base fuel)	0.5	1.6	236	305	389	700	1521	1982	7a, 7c
		3.0	1	6	61	444	1775	2643	
		5.0	0	1	3	9	98	1746	
Blend 3 5% 1-methylnaphthalene/ 95% isooctane	0.5	1.6	260	346	450	770	1482	1612	7d
		3.0	0	5	61	429	1532	1991	
		5.0	0	1	2	6	90	1399	

^aAt $\phi = 0.3$, data rates were less than 1 Hz at all locations for all fuels.

and for all fuels and conditions tested is listed in Table II.

To validate the optical system, the optical probe was positioned at the entrance of an extractive probe used previously.⁴ The extractive probe was located at an axial location ($x/R = 5.0$) and radial location ($r/R = 0.83$) well displaced from the centerline where flow perturbation is minimized. A scanning electron microscopy analysis of the extracted sample was compared to the optical data.

The morphology of the soot (Fig. 5a) is spherical particles ($\sim 0.05 \mu\text{m}$) and agglomerates of the spherical particles (~ 0.1 to $0.4 \mu\text{m}$) which is consistent with the morphology and size observed in other combustor studies (e.g., [4, 14, 15]). An example of the size distribution derived from a scanning electron micrograph (SEM) of the extracted sample is compared to the optical measurement in Fig. 5b. The range of particle sizes resolved by the $60^\circ/20^\circ$ intensity ratioing technique (1) is at the large particle end of the SEM distribution, (2) encompasses the agglomerates, and (3) excludes the primary particles. In terms of mass density, the optical data reflect approximately seventy percent (70%) of the SEM distribution. The difference is attributed primarily to the upper limit ($\sim 0.4 \mu\text{m}$) on the optical window which filters the large (relatively heavy) particle wing of the distribution. In addition, the small (relatively light) primary particles are excluded from measurement, and the validation logic of the software invalidates some scores such as those that occur from multiparticle scattering.

Soot Field

The utility of a point measurement is the ability to map the combustor for soot size and population. An example of such a mapping is presented in Fig. 6a for the base fuel at $\phi = 0.5$. Radial profiles of optically-measured soot size and population are presented at three axial locations within the combustor. Radial and axial locations are nondimensionalized to the combustor radius ($R = 40 \text{ mm}$). All the histograms in Fig. 6a are normalized to the peak bin data rate in the set ($x/R = 3.0$; $r/R = 0.83$). To assist in comparing the histograms in the three-dimensional plots, the histogram with the peak bin data rate in the field is reproduced and dimensioned in the upper left corner of each plot.

The aerodynamic and temperature fields are presented in Fig. 6b. The recirculation zone extends one duct diameter downstream and consists, for this combination of swirl strength and nozzle condition, of a double vortex surrounding a positive velocity on the centerline. The thermal map shows a uniform, high temperature core with a radially diverging steep gradient to a relatively cool, outer flow.

At $x/R = 1.6$, the agglomerate population measured by the optical probe is low and uniformly dis-

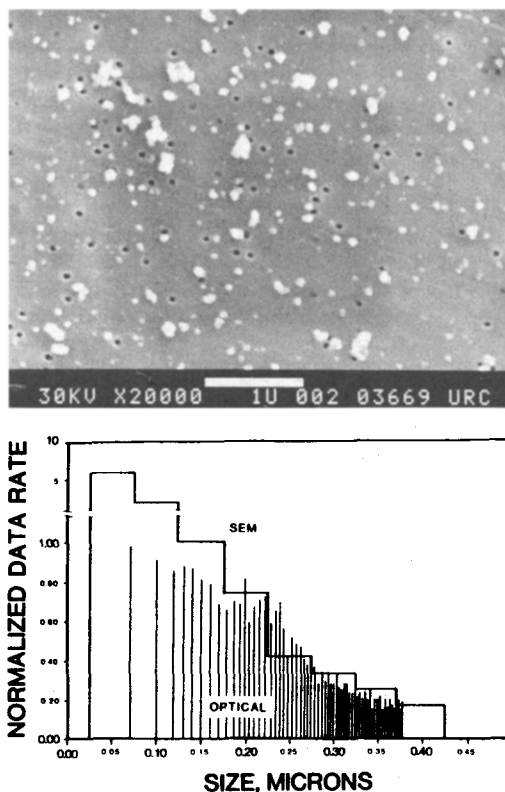
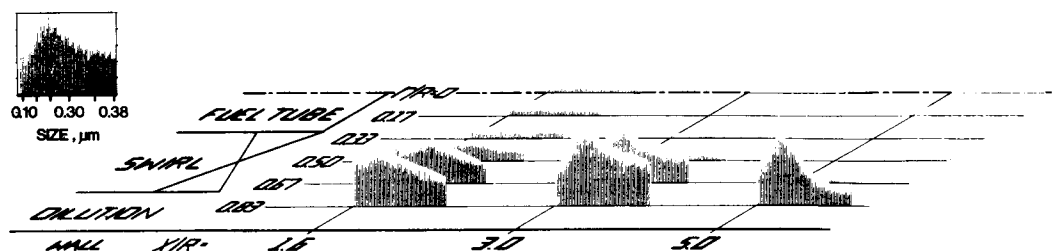


FIG. 5. SEM validation. Comparison of an extracted soot sample to optical measurement taken simultaneously at entrance of probe (isooctane/tetralin, $\phi = 0.5$, $r/R = 0.83$, $x/R = 5.0$): (a) Scanning electron micrograph; (b) comparative histogram.

tributed at the three interior radial positions ($r/R = 0.0, 0.17, 0.33$) that are aligned with the relatively high temperature, well-mixed recirculation zone of the combustor. The agglomerate population at the three outer radial stations ($r/R = 0.50, 0.67, 0.83$) increases as the temperature drops and the residence time increases. The population reaches the maximum in this data set at the exterior radial station at the second axial location ($x/R = 3.0$). The soot in the core of the combustor has been essentially burned out (Table II). At the third axial station ($x/R = 5.0$), the soot is burned out as the temperature increases radially inward. At the $r/R = 0.83$ station, the temperature is not yet sufficient to completely burn out the soot, but the large particle wing of the soot particulate is noticeably reduced, as well as a significant (though less substantial) reduction of the small particle wing. The extent to which this may be attributed to burnout and/or a reorientation of the soot structure is not yet established.

(a) Soot Field



(b) Aerodynamic and Temperature Field

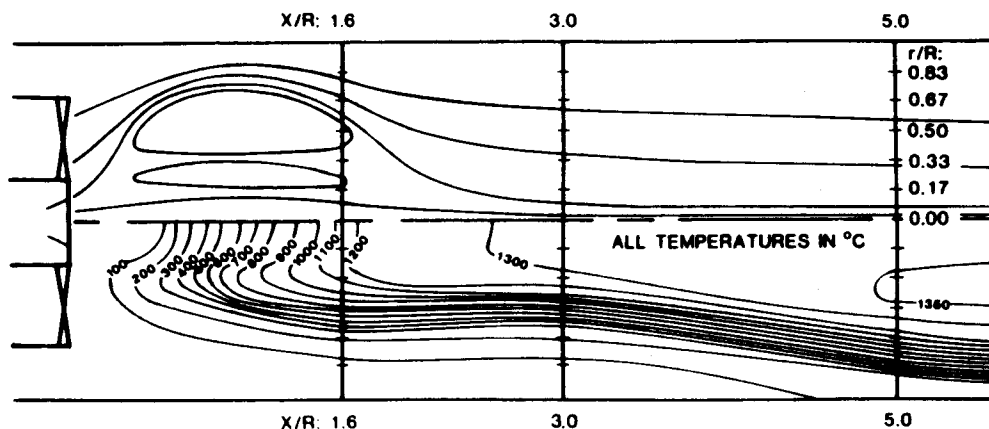


FIG. 6. Spatial maps. Comparison of optically measured soot field to aerodynamic and temperature field obtained by laser anemometry and thermocouple probe respectively (isooctane/tetralin, $\phi = 0.5$): (a) Soot field; (b) aerodynamic and temperature field.

The oxidation of soot in regions of elevated temperature is consistent with the hypothesis that, in premixed flames, the oxidative attack on soot increases faster than pyrolysis as the temperature is raised.¹⁶ Whether the present burner behaves as a premixed system is, at present, a point only of conjecture. Although the burner, in fact, comprises a myriad of diffusion-limited and premixed parcels, the combination of the intense fuel/air mixing, fine atomization, and the efficient distribution of fuel provided by the air-assist nozzle is conducive to the promotion of an overall premixed behavior. (The burner can be driven to a diffusion-type character by a reduction in the atomizing air-to-fuel ratio which results in larger droplets and a collapse of a portion of the fuel onto the centerline to form a fuel-rich combustor core.^{9,11})

Fuel Molecular Structure

The results for the effect of fuel molecular structure on soot size and population are presented in Fig. 7 for isooctane and the three blends (79% isooctane/21% toluene; 92% isooctane/8% tetralin;

95% isooctane/5% 1-methylnaphthalene) prepared to yield the same smoke point. The data are normalized to the peak bin data rate observed for the isooctane/tetralin blend (Figs. 6a and 7c). The total data rates for each location are tabulated in Table II.

The spatial distribution of the soot field is similar for all fuels tested, namely the presence of soot at all radial stations at the $x/R = 1.6$ axial station, but only at the outer radial stations at $x/R = 3.0$ and 5.0 . The data rates for the blends are higher, however, when compared to the pure isooctane. Hence, the addition of ring compounds (as small as 5% by volume in the case of 1-methylnaphthalene) has a substantial impact on the soot produced. Finally, the fuel blends, mixed to the same smoke point, produced different soot yields (area weighted soot flux) at the last axial plane sampled ($x/R = 5.0$, Figs. 7b, c, d). The double-ring tetralin and 1-methylnaphthalene blends both yielded a higher soot level than the single-ring toluene blend. The tetralin blend yielded the highest production of the three.

Data were also obtained at a reduced fuel load-

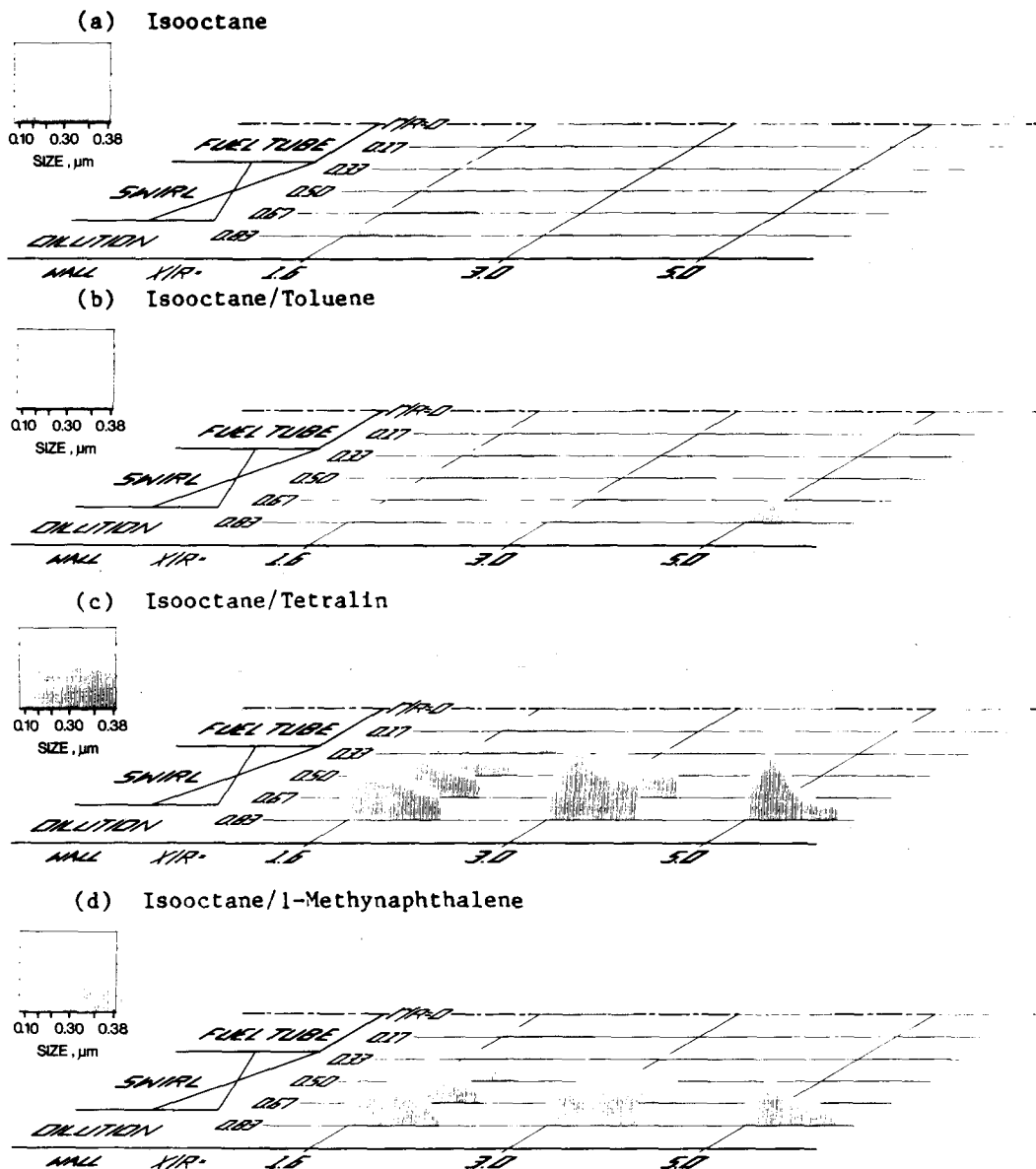


FIG. 7. Fuel molecular structure. Comparison of optically measured soot field for aromatic blends in iso-octane mixed to the same smoke point ($\phi = 0.5$): (a) Iso-octane; (b) iso-octane/toluene; (c) iso-octane/tetralin; (d) iso-octane/1-methylnaphthalene.

ing ($\phi = 0.3$) for the iso-octane and three fuel blends. Little, if any, soot particulate was detected by the optical probe at all of the eighteen sampling points within the combustor (e.g., total data rates were less than 1 Hz) at all stations.

Summary and Conclusions

An optical system based on large angle intensity ratioing has been used to measure soot particulate in an aerodynamically complex flowfield represent-

ative of a practical turbine combustor. The utility of such a diagnostic tool is the provision of detailed mapping to identify the regions of soot formation and burnout. To demonstrate the utility and applicability of the technique, a parametric variation on fuel molecular structure and fuel loading was performed. For the present model complex flow combustor, twin-fluid atomizer design, and operating conditions, blends of ring compounds in iso-octane (as little as 5% 1-methylnaphthalene) produced substantially more soot than the iso-octane alone. In ad-

dition, the soot yield varied among blends mixed to the same smoke point, with the multi-ring tetralin and 1-methylnaphthalene blends producing substantially more soot than the single-ring toluene blend. Three principal conclusions result from this study:

- First, the spatial distribution of soot and the total soot yield in complex flow combustors are themselves complex processes, as much dependent on the combined aerodynamics and fuel distribution in the combustor as on fuel molecular structure. Spatially-resolved, noninvasive optical measurements will be required to guide combustor design, nozzle design, and fuel property specification for future fuels.
- Second, the evidence from the present study indicates that temperature is the principal variable affecting soot yield, and the extent to which aerodynamics and fuel distribution can be combined to process the soot away from regions of relatively low temperature (e.g., dilution jets, walls) will reduce the yield.
- Third, for results derived from noninvasive optical measurements in aerodynamically complex flows to be of quantitative as well as qualitative value, optical techniques must be pursued to extend the resolvable size to encompass sizes approaching $0.05 \mu\text{m}$.

Acknowledgments

The results presented were obtained in a soot formation/alternative fuels study in progress at the UCI Combustion Laboratory and supported by the Air Force Engineering and Service Center, Research and Development Directorate, Environics Division (Air Force Contract FO-8635-83-C-0052) with Captain Paul Kerch as the project manager. The authors gratefully acknowledge (1) the assistance of Roger Rudoff, Kevin Hopkins, and Masanao Yanagihara in the collection, reduction, and presentation of the data, (2) the assistance of Tom Jackson and Robyn Charles for their work in the spray analysis of the Parker-Hannifin twin-fluid injector, (3) the cooperation of Parker-Hannifin in the provision of the nozzle and the valuable technical discussions with Mr. Harold Simmons and Mr. Curt Harding, and (4) the kindness of KVB Engineering and Dr. Larry Muzio for providing use of the Malvern droplet analyzer. The optical particulate measurement system was developed under subcontract to Spectron Development Laboratories with Dr. Chie Poon serving as the principal in the design.

REFERENCES

1. PRADO, G. P., LEE, M. L., HITES, R. A., HOULT, D. P., AND HOWARD, J. B.: Sixteenth Symposium (International) on Combustion, p. 649, The Combustion Institute, 1976.
2. WYATT, W. R., CLARK, J. A., PETERS, J. E., AND MELLOR, A. M.: *J. Energy*, 3, 285 (1979).
3. HIMES, R. M., SAMUELSEN, G. S., AND HACK, R. L.: *J. Engr. Gas Turb. Pwr.*, 106, 103 (1984).
4. HACK, R. L., SAMUELSEN, G. S., POON, C. C., AND BACHALO, W. D.: *J. Engr. Pwr.*, 103, 10 (1981).
5. D'ALESSIO, A.: *Particulate Carbon—Formation During Combustion* (Siegla, D. C. and Smith, G. W., Eds.), p. 207, Plenum Press, 1981.
6. BONCZYK, P. A.: *Combust. Flame*, 51, 219 (1983).
7. HAYNES, B. S., JANDER, H., MATZING, H., AND WAGNER, H. GG.: *Combust. Flame*, 40, 101 (1981).
8. SAMUELSEN, G. S., WOOD, C. P., AND JACKSON, T. A.: *Optical Measurements of Soot Size and Number Density in a Complex Flow, Swirl-Stabilized Combustor*. AGARD Conference Proceedings No. 353, *Combustion Problems in Turbine Engines*, AGARD-CP-353, 1983.
9. WOOD, C. P., AND SAMUELSEN, G. S.: *Optical Measurements of Soot Size and Number Density in a Spray-Atomized, Swirl-Stabilized Combustor*. ASME paper 84-GT-153, 1984, to be published in *J. Engr. Pwr.*
10. BRUM, R. D. AND SAMUELSEN, G. S.: *Assessment of a Dilute Swirl Combustor as a Bench Scale, Complex Flow Test Bed for Modeling, Diagnostics, and Fuels Effects Studies*, AIAA Paper 82-1263, 1982.
11. JACKSON, T. A., AND SAMUELSEN, G. S.: *An Evaluation of Fuel Spray Performance in a Swirl Stabilized Combustor Using Optical Methods for Drop Sizing*, AIAA Paper 84-1318, 1984.
12. KIOKA, L. M., BRUM, R. D., AND SAMUELSEN, G. S.: *Combust. Flame*, 49, 155 (1983).
13. SEILER, E. T.: *Compensated Thermocouple Measurements in a Complex, Reacting Flow*, M. S. Thesis, University of California, Irvine, 1983; also available as UCI Combustion Laboratory Report ARTR-83-11, Mechanical Engineering, University of California, Irvine, Ca, 92717.
14. SAWYER, R. F.: *Emissions From Continuous Combustion Systems* (W. Cornelius and W. G. Agnew, Eds.), p. 243, Plenum Publishing Co., 1972.
15. FENTON, D. L., LUEBCKE, E. H., AND NORSTROM, E.: *Physical Characterization of Particulate Material From a Turbine Engine*, ASME Paper 79-GT-179, 1979.
16. GLASSMAN, I., AND YACCARINO, P.: *Eighteenth Symposium (International) on Combustion*, p. 1175, The Combustion Institute, 1981.

COMMENTS

A. D'Alessio, *Univ. of Naples, Italy*. Soot particles number concentration may easily exceed 10^8 cm^{-3} in the soot forming regions of spray flames.¹ What is the maximum number concentration your method is able to detect? Furthermore how do you discriminate between submicronic soot particles and fuel droplets which might be present in the measurement volume?

REFERENCE

1. BERETTA, F. ET AL.: Eighteenth Symposium (International) on Combustion, p. 1091, The Combustion Institute, Pittsburgh, 1981.

Authors' Reply. The maximum soot particle number concentration measured in the present experiment was $2 \times 10^4 \text{ cm}^{-3}$. The upper limit of the present instrument, as configured, has not been formally established but is estimated to be 10^6 cm^{-3} . With refinements, the instrument may be able to achieve single point counts in particle concentrations as high as 10^7 cm^{-3} . Above this level, ensemble measurements must be made and size distributions must therefore be assumed (Reference 6 in the text). A soot particle number concentration of 10^8 cm^{-3} , although representative of levels reached in oil sprays of relatively low mixing intensity, is unlikely to be reached in the highly mixed regions of a turbine combustor.

The first axial station selected for soot measurements in the present experiment is downstream of the droplet region. Measurements have been made in the spray zone, and most drops scatter with sufficient intensity to be rejected by the ratio processor during data acquisition. For the droplets that scatter with a combination of intensity and intensity ratio similar to the soot, the droplets are discriminated by an intensity validation routine applied during data reduction.

A. Gupta, *Univ. of Maryland, USA*. Mean soot size reported in your paper appears to be much larger than that expected in turbulent diffusion swirling flames. Is this due to your technique used which may have low sensitivity in the lower size range? Also did you make a comparison between the optical method and the physical probe data analyzed with SEM?

Authors' Reply. We do not report mean soot size but instead report the soot size distribution in the window 0.08–0.38 microns. Comparison to SEM data

has established that this window encompasses the large particle wing of the actual distribution (see text of paper) but does not encompass the primary particle peak which occurs at approximately 0.05 microns. Hence, a mean soot size calculated from the optical data would reasonably represent the actual mean soot size on a weight basis, but would yield an erroneously large mean soot size on a number basis. The measured size of the particles is in agreement with the limited data available from gas turbine type combustors (References 14 and 15 in the text).

C. Okoh, *Univ. of Calif., USA*.

- 1) What are the typical radial temperature gradients in your system?
- 2) What are the typical radial velocities?
- 3) From your slides, the temperature gradients are about 10^4 to 10^5 (K/m). This implies significant thermophoresis. What effect does thermophoresis have on your soot profiles at large radial positions (at cooler locations)?

Authors' Reply. The maximum radial gradient of temperature was 11,000 K/m. Radial velocities were not measured in the present experiment. For the two components measured, typical values in the thermal gradient zone were 20 and 10 m/s for the axial and azimuthal components, respectively. Thermophoresis will act to promote the transport of soot from the hotter to the cooler region. For the conditions of the present experiment, the thermophoretic velocity is estimated to be on the order of 10^{-4} m/s. No evidence of soot buildup was detected along the cooler outer radial locations at successive axial locations downstream of the recirculation zone.

G. Andrews, *Univ. of Leeds, England*. You have developed an excellent diagnostic system for inflow soot-size and have demonstrated the importance of combustion aerodynamics on soot formation. However, although your aerodynamics are strong, the turbulence levels are not. Your air velocities and swirler blockage are too low to generate realistic turbulence levels. Soot formation is strongly dependent on turbulent mixing as well as aerodynamics and fuel placement. For the lean overall equivalence ratio of your system, with realistic turbulence levels, you should have been able to eliminate almost all soot formation. In our swirl flames,^{1,2} in a rig similar to yours, we can achieve mixing situa-

tions where negligible soot is generated even with gas-oil as the fuels.

REFERENCES

1. AHMAD, N. T. ET AL.: This symposium.
2. AHMAD, N. T. AND ANDREWS, G. E.: "Gas and Liquid Fuel Injection into an Enclosed Swirling Flow" ASME Paper No. 84-GT-98.

Authors' Reply. The blockage of the swirler in the present experiment is 100%. This is, in fact, comparable to the blockage ("solidity") of 100% utilized in practical combustors. The reference velocity (7.5 m/s) and stoichiometry in the recirculation zone ($\phi \cong 1.0$) are also realistic. Two aspects of the present experiment are not realistic—pressure and inlet temperature—both of which are important to the production of soot.

Reduction of soot was not the objective in the present experiment. Rather, the objectives were to (1) evaluate the utility and limits of applicability of an optical instrument to measure single particles in a combustor with complex aerodynamics, and (2) establish the velocity and thermal characteristics of the combustor to facilitate an understanding of the soot formation and burnout. This information, coupled with measurements of species concentration, is required to establish (1) where and how the soot is formed and burned out within these flows, and (2) the reasons soot is emitted under some combustor and nozzle operating conditions and not under others. In tests where operating and fuel conditions have been systematically varied in the present combustor, nozzle performance and fuel injection state, as well as the swirl strength, are shown to have a profound impact on both the spatial distribution of soot and the total amount of soot emitted (Reference 9 in the text).

D. Olson, Aero Chem Research Labs, Inc., USA. You have found different amounts of soot produced by fuel mixtures which have been blended to have equal smoke points. We have proposed^{1,2} that smoke points be corrected for the oxygen required to burn one mole of fuel when comparing the relative sooting tendencies of various fuels in diffusion flames. Thus two fuels with equal smoke points would be expected to produce the same amount of soot only if their oxygen demands per mole of fuel (which can be closely approximated by using the fuel molecular weights) were the same. We have also formulated a relative scale of sooting tendencies based on the parameter, (molecular weight/smoke point), and have made data available for more than 100 fuels. When one compares fuels with different av-

erage molecular weights, as you have done, equal smoke points do not mean equal tendencies to soot. For example, in our work,² xylene (molecular weight 106 g mol⁻¹) and cyclohexylbenzene (160 g mol⁻¹) have equal smoke points, 0.7 cm, but their relative tendencies to soot differ by almost a factor of 2.

You might compare fuel blends in future work on this basis.

REFERENCES

1. CALCOTE, H. F. AND MANOS, D. M.: *Combust. Flame* 49, 289 (1983).
2. OLSON, D. B., PICKENS, J. C. AND GILL, R. J.: *The Effects of Molecular Structure on Soot Formation. II. Diffusion Flames*, submitted to *Combust. Flame*, June 1984.

F. Takahashi, Princeton Univ., USA. An experiment performed at Princeton¹ has revealed that the tendency of hydrocarbon fuels to form soot under premixed conditions increases with (1) decreasing flame temperature, (2) increasing the number of fuel carbon atoms, (3) increasing the fuel C/H ratio, and (4) increasing the number of unsaturated C—C bonds.

The last three factors of the fuel structure can be characterized by a single parameter, the "number of C—C bonds" where a double bond is counted as two and a triple bond as three. The soot loading behavior in your combustor indicates similar trends with our results on premixed flames rather than diffusion flames where higher temperature produces more soot. Under this condition, can the smoke point for diffusion flames be used as an experimental parameter?

REFERENCE

1. TAKAHASHI, F. AND GLASSMAN, I.: *Combust. Sci. Tech.* 37, 1 (1984).

Authors' Reply. Smoke point was selected for blending (1) as a point of departure due to the historic use of smoke point as an index of the sooting tendency of fuels in turbine combustors, and (2) to provide empirical evidence for the correspondence, if any, between the smoke point and the sooting tendency of a fuel in an aerodynamically complex flow.

The smoke point (the height at which sooting is first observed in a diffusion flame) should be questioned as a correlation parameter for the soot production in a complex flow. Indeed, smoke point does

not correlate with the sooting propensity in the present case. Cases do occur, however, where smoke point does correlate in complex flows over a wide range of fuel molecular structure. Examples include tests in the present combustor when the fuels are introduced prevaporized,¹ and tests with fuels injected as liquids into a turbine combustor at elevated pressure.²

In spray-injected, swirl-stabilized flows, a myriad of fuel/air parcels is produced, some of which react premixed and some of which are diffusion limited. Further, turbulent mixing, as well as reaction, change the composition of the parcels during transport. New parcels are formed, others are removed. Sooting propensity, as a result, depends on the time-temperature-composition history of the ensemble of parcels which, in turn, depends on the combustor operating conditions, the manner in which the fuel is introduced, and the fuel properties.

Future work will include alternative proposals for blending to assess whether, independent of combustor design and operation, a rating procedure exists that describes the sooting tendency of a fuel in a complex flow. The effect of nozzle performance, swirl strength, and fuel inlet state observed in the present model combustor³ suggests that the evolution of such a rating system, if successful, will be limited to a specific device and will not be universal in geometry.

REFERENCES

1. Reference 8 in the text.
2. ROSJFORD, T. J.: *Aviation-Fuel Property Effects*

on Combustion, NASA CR-168334, February, 1984.

3. Reference 9 in the text.



G. Greeves, Lucas Cav Limited, England. Our experience with diesel combustion is that local soot formation is strongly dependent on the local equivalence ratio. For example, you state in the abstract that soot formation was relatively high in regions of depressed temperature. This may not be because the temperature was depressed, but because of a sufficiently fuel-rich mixture. Did you plan to measure local equivalence ratio or species concentrations?

Authors' Reply. Available oxygen, as well as temperature, is important to both the formation and destruction of soot. Local measurements of species concentration are planned using an extractive probe. In flows of this type, measurements with an extractive probe must be qualified and are therefore not sufficient to draw clear conclusions.^{1,2} An optical measurement is preferred to avoid perturbation of the aerodynamic and thermal field. The ability to optically measure temperature and species concentrations in complex flows is now evolving.

REFERENCES

1. Reference 4 in text.
2. LARUE, J. C., SAMUELSEN, G. S. AND SEILER, E. T.: Twentieth Symposium (International) on Combustion, The Combustion Institute, 1985.