Electrostatic Spray Modification in Gas Turbine Combustion

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The feasibility of using electrostatic fields as a practical means of altering existing gas-turbine-injector spray characteristics has been investigated. Results indicate that with electrical potentials typical of spark plug voltages, a significant modification of spray characteristics in terms of average droplet size reduction and increased spray cone angles can be produced. This suggests a means of expanding the utility of present combustors either by broadening the operating range for optimum performance with the design or by permitting more attractive combustion of nondesign fuels. A simple retrofit during engine overhaul would allow present combustors to operate with or without electrostatic spray modification.

Nomenclature

C_v = spray concentration by volume, dimensionless
D_{32} = Sauter mean diameter, μm
ER = equivalence ratio, dimensionless
I = current, A
$\bar{K}$ = mean Mie scattering coefficient, dimensionless
ℓ = extinction length, cm
t = transmissivity of light, dimensionless
T = temperature, °C
V = accelerating potential, volts
x = electrode gap, mm
$\Delta\eta$ = change in combustion performance, dimensionless
η^* = combustion effectiveness parameter, dimensionless

Introduction

BECAUSE combustion efficiency directly affects propulsive efficiency, substantial effort has been devoted to the development of fuel injectors that produce the optimum droplet size and dispersion pattern in order to maximize the combustion efficiency of each application. As a consequence of the changing market for refined pertroleum products, refiners have tended to alter their jet fuel composition to include heavier fractions. This trend in blending produces fuels of greater viscosity and surface tension, lower vapor pressure, and also results in sprays characterized by larger droplet sizes with altered dispersion patterns. The present work reports on an investigation into the feasibility of using electrostatic fields to modify droplets' size and dispersion patterns in order to reoptimize these quantities when fuels, other than those for which a given combustor has been designed, must be burned.

Efficiencies of present combustors are high, and current sentiment is that combustion efficiencies will remain high with alternate fuels. But efficiency does not represent the entire picture in combustion performance. A study done by General Electric[1] evaluating fuel character effects on a turbojet engine (the J79-17C smokeless combustor) indicates that the relative fuel droplet size, i.e., the parameter directly influenced by the injector, has an effect on 1) CO and HC emissions; 2) cold day ground start light off; and 3) altitude relight limits at low Mach numbers. Nondesign fuels produce larger droplets, which tend to worsen the abovementioned effects, and a technique for refining the spray is desirable. Enhanced atomization could also help at ignition and idle as well as during engine transients. The combustor-can liner is sensitive to the higher heat transfer, which results from the higher flame luminosity arising from larger droplets. Electrostatic breakup of these larger droplets might substantially diminish this effect, thereby increasing liner lifetime.

Received May 6, 1986; revision received July 30, 1986.

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Background

Several workers[2-4] have previously investigated electrostatic effects on droplet size distribution in liquid sprays, both theoretically and experimentally. The principal effects that are likely to influence combustion efficiency are 1) reduction of droplet mean size as well as size distribution, and 2) production of more geometrically refined spray patterns characterized by increased droplet dispersion (cone angle). These effects can be achieved with accelerating potentials of 7-30 kV, typical of spark plug voltages, and currents of the order of 100 ηa for typical gas turbine combustor geometries and fuel flow rates (0.1 liter/s for a single combustor can). These figures suggest the practicality of modifying gas turbine fuel sprays by electrostatic means in order to optimize combustion performance over a wider range of operating parameters. The equilibrium size of spray droplets is a complex function of external viscous and pressure forces that the liquid stream encounters in the nozzle and surface tension forces. If, in addition, electrostatic forces are introduced, a new readily controlled parameter enters into the force equilibrium, which determines droplet size. Electrostatic charging of a liquid droplet produces forces that tends to break the drop, overcoming the surface tension force that tends to preserve it. The energy associated with the surface tension increases when a droplet is split, whereas the energy associated with the electrostatic charge decreases when a droplet is split. If the net energy change represents a decrease in total energy, it is nearly certain that a drop will break up. Moreover, multiple like-charged droplets tend to repel each other, and a second effect produced by electrostatic charging is spreading, which then reduces the tendency of the spray to agglomerate.

Droplets may be charged by transfer (conduction) at the nozzle, by passage through a corona discharge, or by a combination of these two processes. Generally, the corona discharge process is the more effective means of charging spray droplets. The "triode" apparatus of Kelly,[2] which employs this process, is an efficient but complex device, the adoption of which would involve complete redesign of presently operating spray-injector systems. Kelly's triode represents an advancement of the state of the art in electrostatic atomization.

In the present work, a much simpler configuration has been chosen; it depends principally on conduction and to a lesser degree on corona discharge. Its advantage lies first in its direct applicability to existing gas turbine designs and second in its employment of existing spark plug technology using tungsten electrodes and aluminum oxide-silica insulation. The power required, typically 50 W or less, is derivable from current igniter sources with voltage filtering.

The flow of charged droplets constitutes an electrical current in the usual sense. As a consequence, the voltage, which can be sustained in a given application is governed by an "ohms law." Moreover, the proximity of the combustion reaction, with its high electrically conductive products, further limits the electrostatic potential, which can be maintained. These problems pose the principal obstacle to practical implementation of electrostatic control in present gas turbine combustor sprays. The high-voltage probe described herein represents one approach to the solution of this problem. An obvious solution to the abovementioned limits lies in routing the electrode entirely out of the field of combustion products; such a solution will be possible when the integration of electrostatic control is part of the original design process rather than a retrofit.

Experimental Program

Two simultaneous investigations have been carried out in our effort to determine the feasibility of evolving a practical system for the electrostatic control of gas turbine fuel sprays. First, an optical investigation guided electrode design and quantified the effects of electrostatic charging on spray characteristics. Second, a combustor investigation measured the effects of electrostatic spray modification on combustion efficiency in a typical gas turbine.

Optical Spray Diagnostics

A standard Allison T-56 engine nozzle, calibrated to the manufacturer's specifications, was adopted as a base for this investigation. Designed as an injector for JP-4 fuel, its performance with other fuels, including JP-5 and number 2 diesel oil, led typically to larger fuel droplets and reduced-spray cone angles. The properties of the fuels investigated are summarized in Table 1.

In addition to high-speed macroscopic photography of overall spray characteristics, a number of light-scattering techniques are available for the determination of droplet sizes. These range in sophistication (and complexity) from the measurement of Sauter mean diameter[5,6] to the exact determination of droplet size and velocity distribution functions.[7]

In the present work, a relatively simple optical arrangement was first employed, which allowed both high-speed (microsecond) photography of the spray plume as well as a laser light extinction measurement of the relative Sauter mean diameter. The optical experimental setup is shown diagramatically in Fig. 1. With this setup, the effects on spray geometry and droplet diameter as a function of fuel type, injector flow rate, and applied potential could be easily determined.

The photographic portion of this work was carried out with a stroboscopic light which produces flashes of the order of one microsecond and is of sufficient intensity to obtain photographic records, and a 10.16×12.70 cm (4×5 in.) recording camera capable of high resolution.

The laser extinction portion of the experiment employed a 5-mW He-Ne laser whose chopped beam is expanded to 15-mm in diameter, passed through the spray, and then focused by a 60-cm focal-length lens on 100-μm pinhole. The signal is detected by a photodiode incorporated into an operational amplifier. A beam splitter in the laser output is used to provide a reference signal for a lock-in amplifier. This optical arrangement ensures 1) adequate means of detecting even the largest average drop (approximately 1 mm), due to the large beam diameter; 2) full measurement of the diffraction-limited (unscattered) portion of the signal; and 3) filtration of all but a negligible fraction of scattered light, which results in reliable measurement of light transmission. The laser beam transmission may be related to Sauter mean diameter by an expression given by Dobbins et al.[5]:

$$t=\exp[(-2/3)(\bar{K}/D_{32})C_v\ell] \tag{1}$$

where ℓ is the extinction length, C_v the spray concentration by volume, D_{32} Sauter mean diameter, and $\bar{K}$ mean Mie scattering coefficient. For the size range of interest, (>20 μm), Penndorf's[8] approximation leads to a value of $\bar{K}=2.02\pm0.02$, being nearly constant. For constant fuel flow rates, C_v and ℓ become constant and may be eliminated from comparative measurements

$$\frac{\ell n t(V=0)}{\ell n t(V\neq 0)}=\frac{D_{32}(V\neq 0)}{D_{32}(V=0)} \tag{2}$$

More recently, an improved device has been utilized,[9] that can measure particle sizes between 20–200 μm with an uncertainty of less than 4%.

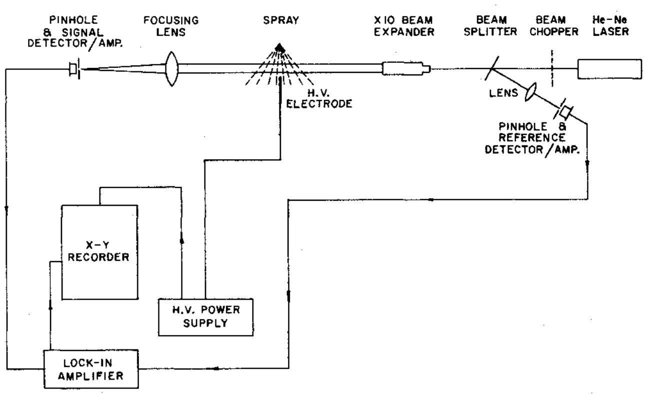

Fig. 1 Schematic diagram of optical experimental apparatus.

Table 1 Summary of fuel properties

Fuel	Hydrogen [c] wt., %	Aromatics[c] volume, %	Density[c], kg/m^3	Kinematic[d] viscosity cst, at 16°C	Surface[e] tension N/m×10^{-c}, at 20°C	Net heat of[c] combustion, MJ/kg
JP-4[b]	14.1	14.1	755	1.03	23.5	43.4
JP-5[a]	13.3	22.7	827	2.2	29.0	42.9
JET-A[b]	13.4	18.9	822	2.1	25.6	43.0
DF-2[b]	12.3	48.5	870	8.0	28.8	42.4
JET-A[a]	13.4	22.3	827	2.1	31.3	43.0
DF-2[a]	12.7	67.0	861.5	7.5	42.4	42.6

[a]Batch used through Dec. 1982. [b]Batch used after Dec. 1982. [c]Analysis performed by Energy Management Laboratory, Wright-Patterson Air Force Base (Ref. 13). [d]Data from above source, adjusted for temperature (Ref. 14). [e]By capillary tests.

Combustion Experiments

A single Allison T-56 combustor-can liner, with its associated injector nozzle, was used to measure the effects of electrostatic spray modification on the combustion effectiveness of the fuels listed in Table 1. Figure 2 is a schematic diagram of the combustion apparatus. Air is supplied by a 221-kW (300 hp) vane compressor producing flow rates in the range of 0.05–0.57 kg/s (400–4500 lb/h), that were measured with a calibrated orifice meter. Fuel is supplied from a controllable constant pressure reservoir, producing flows in the range 10–15.5 gm/s (80–125 lb/h), that were measured with a turbine flowmeter. With these air and fuel flow rates, equivalence ratios from 0.3–0.6 and 2.0–4.4 were investigated. Due to the pressure ratio limitation of the air supply, the combustor was operated at relatively low inlet temperatures [~55°C (130°F)] and pressures (1 atm). The effect of these limited parametric values on the validity of the simulation has yet to be ascertained.

Combustor exhaust temperatures were measured by three shielded chromel-alumel thermocouples, distributed over the exit plane (at available thermocouple insert ports), which were recorded individually and as a sum average on a strip-chart recorder. A separate platinum-platinum-rhodium thermocouple was used for redundancy. No attempt was made to correct thermocouple data for losses.

The high-voltage electrodes were introduced into the combustor liner either through a "crossover port" or one of two specially constructed ports as shown in Fig. 3. The high-voltage electrodes were mounted in a ball joint in order to permit adjustments in electrode-nozzle gap and electrode orientation. An optical periscope system was fabricated and used to locate the electrode precisely within the burner can.

Special attention was paid to the elimination of electrical noise generated by the presence of the high-voltage system in the electronic instrumentation.

Results

Optical Experiments

The optical experiments were intended to produce two results: to guide electrode design and to quantify the changes that could be produced by electrostatic forces. Two distinct electrode geometries were investigated. The first was a single electrode, either blunt or pointed, consisting of a 2-mm tungsten rod with a hemispheric end or a 6-deg included angle, located on the combustor centerline. The second was a ring electrode, consisting of a 2-cm-diam hoop of 2-mm stainless steel, oriented concentrically with the combustor centerline. As might be expected, the single centerline electrode produced a more intense electrostatic field and, as such, was more effective in charging droplets. Of the two single electrodes, the blunted version produced the higher electrostatic fields and the better electrostatic charging of the droplets, whereas the sharply pointed single electrode led to higher corona discharge currents, thereby charging the droplets by diffusion in the spray.

In a typical run, in which a single-pointed electrode located 8 mm from the nozzle face was injected with JET-A fuel at 620 Kpa (90 psig), a potential of 14 kV produced a decrease in laser light transmission from 0.390 to 0.375, corresponding to a 4% decrease in Sauter mean diameter. C_v and ℓ depend on the droplet number density and on the spray volume. Changes in the spray volume result from the effects of mutual repulsion of like-charged droplets and show as a change in spray-cone angle in Fig. 4. The change in volume was determined from measurements of these photographs. Correction of this result for changes in these parameters produces an actual decrease in Sauter mean diameter of 7%. This result may be compared with that of Kelly,[2] who was able to produce a decrease in most probable drop diameter (a somewhat different measure of mean drop diameter from the Sauter mean diameter) of about 20% for JET-A using the more complex triode arrangement.

The high-speed photographs of Fig. 4 confirm that the measurements of drop size reduction and the reduction of the

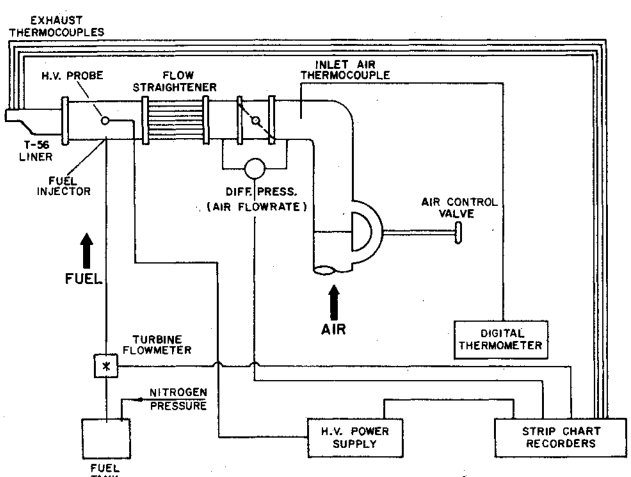

Fig. 2 Schematic diagram of the combustion apparatus.

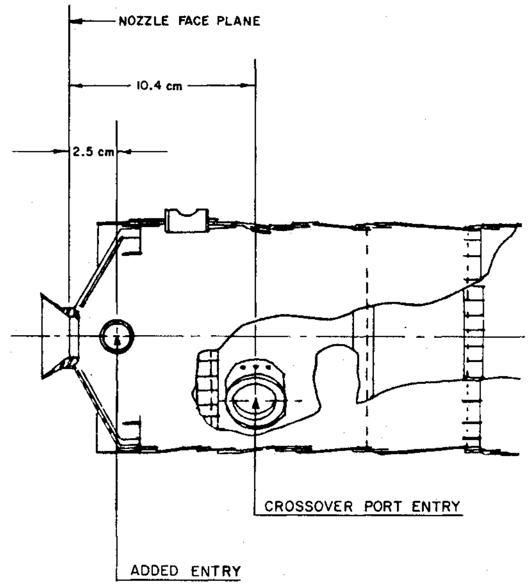

Fig. 3 Probe entry locations.

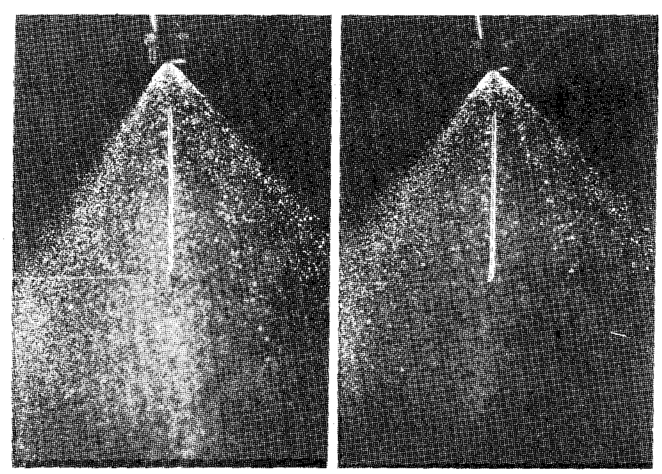

Fig. 4 Modification of spray characteristics by electrostatic potential.

Table 2 Summary of results of the combustion experiments

Test%	Fuel	ER	V kV	I mA	x (gap) mm	T °C	η,* %	Remarks
4-21-7	JET-A[b]	0.38	4.0	very low	7.5	923	3.3	Sharp point,
4-21-10	JET-A[b]	0.36	4.0	very low	7.5	845	6	quartz-sealed probe
4-21-11	JET-A[b]	0.39	4.6	low	7.5	922	4	
4-21-12	JET-A[b]	0.355	4.6	low	7.5	858	10	
4-21-13	JP-4[b]	0.4	4.4	low	7.5	942	6.67	
4-12-14	JP-4[b]	0.36	4.0	low	7.5	877	6.25	
5-17-18	JP-4[b]	0.38	8	4.5	20	900	7.64	Blunt, double-insulated
5-17-19	JP-4[b]	0.345	8	4.5	20	836	11.43	purged probe
5-18-2	JP-4[b]	0.345	9	5.0	25	826	14.29	
5-20-1	JP-4[b]	0.395	10	4.5	35	900	5.0	
5-20-2	JP-4[b]	0.36	9	4.5	35	855	10.71	
5-13-11	DF-2[b]	2.44	4	5	9	1113	8.3	
5-17-12	DF-2[b]	0.45	8	1÷2	15	968	2.35	
5-17-13	DF-2[b]	0.39	8	1÷2	15	850	7.93	
5-17-14	DF-2[b]	0.37	8	1÷2	15	836	4.07	
5-17-26	DF-2[b]	0.36	8	4.5	20	843	5.22	
5-18-10	DF-2[b]	0.39	9	4.5	25	883	6.2	+0.75%, based
5-20-14	DF-2[b]	0.38	7	low	7.5	883	6.82	on $\Delta T_{\text{“}R\text{”}}/3$
5-20-14	DF-2[b]	0.38	6	low	7.5	883	6.82	
5-20-14	DF-2[b]	0.38	4	<0.2	7.5	883	6.82	(same probe)
10-29-10	DF-2[a]	2.8	10	<5.0	25	1150	25	Shape point, purged probe
10-29-10	DF-2[a]	2.8	10.3	5.0	25	1150	13	(all following tests)
10-29-11	DF-2[a]	2.8	10	<5.0	25	1150	20	
11-2-2	DF-2[a]	3.1	10.5	<5.0	25	1150	25	
11-2-3	DF-2[a]	3.45	10	<5.0	25	1100	25	
11-2-4	DF-2[a]	4.27	10.9	<5.0	25	1050	29	
11-2-6	JP-5[a]	2.94	11.4	<5.0	25	1188	5.83	
11-2-7	JP-5[a]	4.4	11.4	<5.0	25	1010	6.7	
11-2-8	JP-5[a]	0.475	10.3	<5.0	25	790	14	
11-4-1	JP-5[a]	0.417	10.5	<5.0	25	760	11	
11-4-2	JP-5[a]	0.415	10.8	<5.0	25	760	7	
11-4-3	JP-5[a]	0.419	10.3	<5.0	25	775	5	
11-4-8	JET-A[a]	0.47	10.0	<5.0	25	809	10	
11-4-11	JET-A[a]	0.53	10.0	<5.0	25	955	4	
11-4-12	JET-A[a]	2.86	10.2	<5.0	25	1090	20	
11-5-1	JET-A[a]	3.3	11.1	<5.0	25	1120	9.2	
11-5-2	JET-A[a]	3.35	10.8	<5.0	25	1090	10	

[a]Batch used through Dec. 1982. [b]Batch used after Dec. 1982.

number of large droplets (diameters >600 μm), under the influence of electrostatic fields, is marked.[10]

A great deal of data were collected, whose principal value was to provide guidance to the combustion experiments. Perhaps of more practical significance was the ability to produce sprays, of No. 2 diesel fuel, which closely emulated the characteristics of the design fuel JP-4 over a significant portion of the injector-operating envelope, solely through the adjustment of electrostatic potential.

Combustion Experiments

The first result of the full-scale combustor experiments was the confirmation that the proximity of combustion gases to the electrode constituted a sufficiently low electrical path that led to excessive currents, i.e., to exceeding power supply characteristics. As a consequence, substantial effort has to be devoted to the design of electrodes and electrode supports to overcome this problem. What evolved were several high-voltage electrode-probe configurations, two of which are shown in Fig. 5. These were constructed much like spark plugs, using a center electrode of tungsten insulated both thermally and electrically from the combustion gases with sheaths of quartz and ceramic. In addition, it was found desirable to minimize the flame-holding characteristics of the probes by purging them with small quantities of nitrogen, which was ejected through flame blow-off slots, as indicated in Fig. 5a. (Alternatively, a sealed nitrogen-pressurized probe shown in Fig. 5b was found to be equally effective for some probe positions because of its low flameholding profile.) Improved probe designs are expected to result from further work.

Although the best-performing probe-electrode designs were not able to support continuous voltages significantly greater than 11 kV without either excessive leakage current or arc breakdown, a measurable improvement in combustion effectiveness was obtained for all electrode voltages. These results are summarized in Table 2. While average exhaust gas temperature increased for all fuels with the application of high voltage, there is a trend toward greater increase in combustion efficiency over a wider range of operating conditions for the higher-viscosity and higher-surface-tension fuels. These fuels also exhibited lower initial combustion efficiency than did JP-4, as would be expected. The ability to start the combustor with the diesel fuel and to partially clear up the "black smoke" bears special mention here. The results for fuel-rich runs have been included in Table 2 even though the thermocouple readings obtained indicate incomplete combustion (i.e., the calculated adiabatic flame temperature at the relevant equivalence ratio was sometimes lower than that measured by the thermocouples).

The results of Table 2 can be best interpreted through introduction of a combustion efficiency increase to the potential for combustion efficiency increase,

$$\eta^* = \frac{\Delta\eta_{\text{COMB}}}{1-\eta_{\text{COMB}}} \tag{3}$$

If we assume that we can ignore the effects of convective and radiative losses [because of the form of Eq. (3), the effects of these assumptions, appearing in both numerator and denominator, tend to be minimized], then the combustor-can exit the combustor-can exit temperatures may be substituted

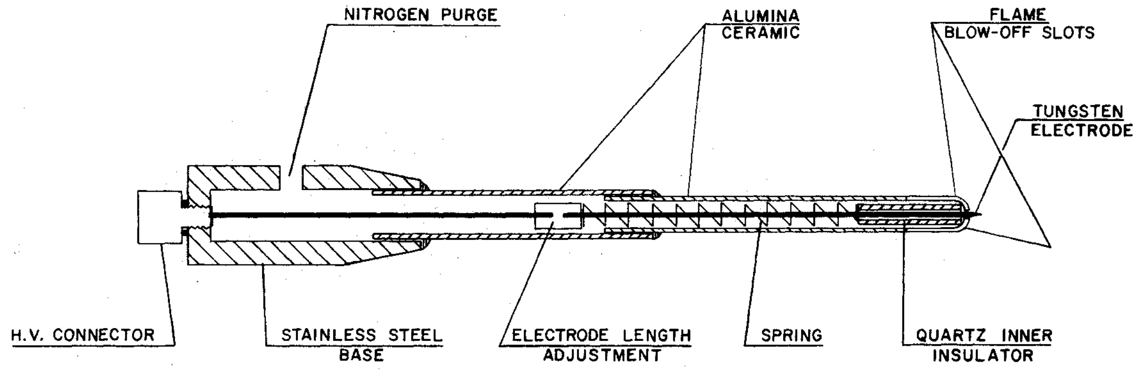

Fig. 5a Double-insulated h.v. probe with flame blow-off control.

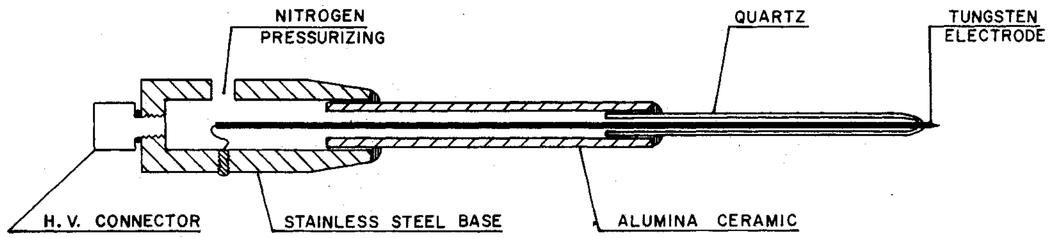

Fig. 5b Sealed-pressurized, quartz insulated h.v. probe.

for actual flame temperatures, and we may write

$$\eta^* = \frac{(T_{AF} - T_O) - (T_{AF} - T_V)}{1 - (T_{AV} - T_O)} = \frac{T_V - T_O}{1 - (T_{AF} - T_O)} \tag{4}$$

where T_{AF} is the adiabatic flame temperature, T_V the flame temperature in the presence of electrostatic effect, and T_O the flame temperature without electrostatic effects. The adiabatic flame temperature was computed from the "PEP code" described in Ref. 11.

The results summarized in Table 2 indicate that at least a modest increase in combustion efficiency resulted in every run of the combustion experiments. The most dramatic improvements appear to be associated with the fuel-rich runs; however, these results probably overstate the improvement since, in general, fuel-rich mixtures were observed to burn well downstream of the combustor exit plane where temperatures were measured. Hence, the measured base-line combustion efficiencies for equivalence ratios greater than unity are lower than actual combustion efficiencies.

The results of the combustion experiments for $ER < 1.0$ are summarized in Fig. 6. As shown, a minimum improvement of 2–3% was obtained, even with the design fuel JP-4. Results with diesel fuel are the most dramatic because its characteristics are the furthest from those of the design fuel. The dependence of η^* on ER is not perceived as particularly meaningful at this point because of the substantial scatter on the uncorrected thermocouple data.

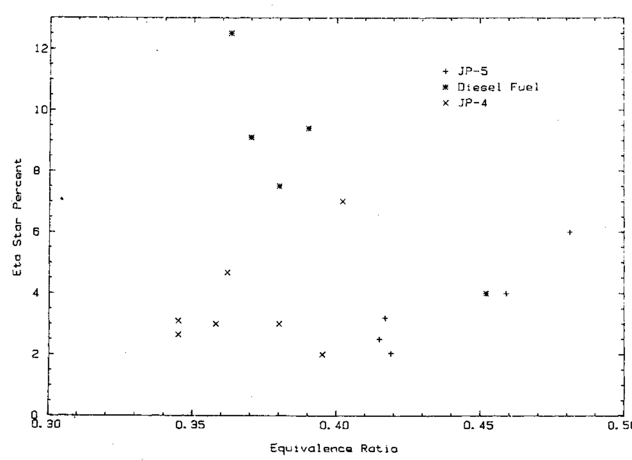

Fig. 6 Effectiveness index vs equivalence ratio.

Discussion and Conclusions

The results reported here confirm those of Kelly[2] and Ito et al.[4] for the electrostatic enhancement of hydrocarbon fuel spray characteristics. A reduction in Sauter mean diameter, as well as a reduction in the number of large-size droplets, was produced by the application of electric fields. Furthermore, the combustion experiments, carried out in an actual gas turbine combustor can, confirmed the assumption that these enhanced spray characteristics would lead to improved combustion performance. The power required to produce these effects is typically of the order of 1% of the additional energy released, and the voltages required are of the order of existing igniter voltage. Because such voltages are easily controlled, it will be possible to "fine tune" an engine for a wide variety of operating conditions as well as for fuel composition. Such control may even be managed automatically by a microprocessor, which senses the engine operating parameters. Enhanced atomization at ignition is certainly of interest.

Although the increases in actual combustion performance reported here are small, combustion efficiencies are already on the order of 90% in modern gas turbine combustors, and even an increase of a few percent represents a substantial fraction of the available margin for improvement. Moreover, the data support the conclusion that the largest improvement in combustion performance and the greatest range over which improvement is observed occurs with the higher-viscosity and higher-surface-tension fuels. These results are consistent with the existing theoretical models that predict larger Sauter mean diameters at higher viscosity and surface tension for both pressure and air-blast atomizers.[6,12] It may be concluded, then, that the greatest potential for improving the combustion efficiency lies in the burning of low-grade fuels during non-optimum combustor-operating conditions. The ability to control undesirable emissions, as well as the possibility of improving light off and relight limits, should not be overlooked.

Although the combustor inlet temperature is somewhat lower than actual gas turbine operating conditions (in terms of absolute temperature), and the combustor operating pressure is substantially lower than actual combustor pressures, the purpose of the present work is to investigate the feasibility of using electrostatic means to enhance spray formation within the restrictions imposed by a limited air supply. Based on the positive results obtained at these reduced pressures, we are encouraged to undertake a full-scale, full-pressure investigation.

Acknowledgment

The authors gratefully acknowledge the support of this work by its sponsor, the Naval Air Systems Command.

References

[1]Gleason, C. C., Oller, T. L., Shayeson, M. W., and Kenworthy, M. J., "Evaluation of Fuel Character Effects on J79 Smokeless Combustor," AFWAL-TR-80-2092, ESL-TR-80-46, Nov. 1980.

[2]Kelly, A. J., "The Electrostatic Atomization of Hydrocarbons," *2nd International Conference on Liquid Atomization and Spray Systems (ICLASS-82)*, Madison, WI, June 1982.

[3]Pfiffer, R. J. and Hendricks, C. D., *Physics of Fluids*, Vol. 10, Oct. 1967, pp. 2149–2154.

[4]Ito, K., Yamane, K., and Fukazawa, S., "Electrostatic Atomization of Liqued Fuels," *Journal of Fuel Society of Japan*, Vol. 51, March 1972, pp. 726–732.

[5]Dobbins, R. A., Crocco, L., and Glassman, I., "Measurement of Mean Particle Size of Sprays from Diffractively Scattered Light," *AIAA Journal*, Vol. 1, Aug. 1963, pp. 1882–1886.

[6]Rizkalla, A. A. and Lefebvre, A. H., "The Influence of Air and Liquid Properties on Airblast Atomization," *Transactions of ASME, Journal of Fluids Engineering*, Vol. 97, Sept. 1975, pp. 316–320.

[7]Bacholo, W.D., Hess, D.F., and Hartwell, C.A., "An Instrument for Spray Droplet Size and Velocity Measurements," *Engineering for Power*, Vol. 102, July 1980, pp. 57–82.

[8]Penndorf, R. F., "An Approximation Method to the Mie Theory for Colloidal Spheres," *Journal of Physics and Chemistry*, Vol. 62, Dec. 1958, p. 1537–1542.

[9]Powers, J., Shavit, Z., Biblarz, O., and Miller, J. A., "Variable Focal Length Radiometer for Particle Sizing," ICIASF '85 Record, IEEE 85, CH2210-3, Aug. 1985, p. 115.

[10]Laib, R. J., "Design of an Apparatus for the Study of Electrohydrodynamic Control of Spray from Fuel Injectors," Engineers Thesis, Naval Postgraduate School, Monterey, CA, Oct. 1982.

[11]Cruise, D. R., "Theoretical Computation of Equilibrium Composition, Thermodynamic Properties and Performance Characteristics of Propellant Systems," NWC TP6037, Naval Weapons Center, China Lake, CA, April 1979.

[12]Longwell, J. P., *Combustion Processes*, edited by B. Lewis, R. N. Pease, and H. S. Taylor, Princeton University Press, Princeton, NJ, 1956.

[13]Yount, N. J., Turbine Fuel Test Reports, Wright-Patterson AFB, Ohio, Energy Management Laboratory, 82-F-2025/2026/2027, Oct. 1982 and 83-F-0541/0542/0543, March 1983.

[14]Stearns, R. F., Johnson, R. R., Jackson, R. M., and Larson, C. A., *Flow Measurement with Orifice Meters*, Van Nostrand, New York, 1951.