Spray Patternation at High Pressure

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The spatial distribution of the fuel spray created by a gas turbine fuel injector has been measured at high pressure and temperature. A patternation system for measuring fuel-spray mass flux distributions at high-power conditions has been designed and operated. The facility has been designed to simulate the environment inside a gas turbine combustor as closely as possible. Results for a full-scale gas turbine fuel injector have been obtained at high levels of pressure, temperature, and liquid flow rate and compared with visual observations and ambient pressure results.

Introduction

THE importance of the fuel-injection process in effective combustor operation and durability has long been recognized. Since fuel is injected from discrete sources, its spatial distribution and subsequent mixing with combustor airflows is most critical. Poor fuel-injector operation will produce adverse fuel/air ratio variations. As a consequence, unacceptable soot concentrations, liner radiation loads, and/or streaks of high-temperature gas entering the turbine could be encountered.

Spray-patternation measurements are useful in the identification of the sources of spray nonuniformities and for the characterization of fuel nozzle behavior over a range of conditions. Because of the influence of the initial spray distribution on the performance of the combustor, patternation measurements are often considered a key step in characterizing combustor nonidealities.

One issue generally not studied by previous fuel-injection investigations is the determination of the behavior of full-size nozzles when subjected to real operating constraints. The majority of previous studies have been performed in the laboratory with relatively small-scale devices. Most often, such studies are performed at atmospheric conditions, in a still environment. How do predictions from such studies relate to a real-gas turbine nozzle spraying at actual operating conditions? Unfortunately, the scaling procedures necessary to perform an atmospheric test that absolutely replicates high-power conditions are not known. Scaling procedures that produce useful trends are confidently used by investigators. However, quantitatively precise scaling laws are not in hand.

Several investigators have focused on the influences of test-chamber pressure and temperature on fuel sprays. Increases in chamber density (most often accomplished by pressure increases) have been shown to reduce the spray cone angle from simplex pressure atomizers[1–3], with Wang and Lefebvre[1] observing a limit in the cone's collapse with increasing pressure. These studies, however, were performed with idealized nozzles and may not be representative of the behavior of more complex large-scale devices. For example, many of these studies concentrated on the sprays produced by simplex atomizers in the absence of any nozzle airflow. These nozzles delivered flows ranging from 3–150 kg/h. In contrast, many real fuel nozzles employ complex, high-velocity airflows and deliver fuel at flow rates up to 500 kg/h.

The objective of this effort was to characterize the fuel sprays produced by several real gas turbine fuel nozzles at conditions typical of those at which the nozzles would operate. Characterization included droplet size and patternation measurement, as well as documentation of spray behavior over a wide range of conditions. The high-pressure spray facility and patternator have been designed in order to investigate the behavior of sprays at real combustor operating conditions. The high-pressure studies focused on the nonidealities of real sprays and on the scaling procedures used to perform tests at atmospheric conditions. The high-pressure spray facility and patternator have been designed in order to investigate the behavior of sprays at real combustor operating conditions. The facility is also used to gage the validity of the scaling procedures used to perform tests at atmospheric conditions. This paper describes the patternation behavior of a dual-orifice pressure atomizer of the type used in many in-service gas turbines.

High-Pressure Spray Facility

A schematic of the gas flows supplying the high-pressure spray facility is shown in Fig. 1. Continuous air flow rates of up to 2 kg/s from a 4000 kPa system were available. For cases where air was not desirable (i.e., when operating with fuel at gas temperatures greater than 400°K), the air supply could be replaced with a high-capacity nitrogen blowdown system. Gas flows could be heated to test-section temperatures of up to approximately 750°K using a high-voltage electric heater. Gas flow rate control was achieved via control of the pressure upstream of a choked venturi. A remote control backpressure

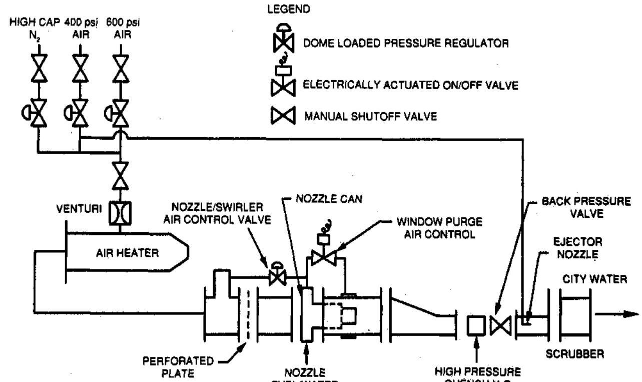

Fig. 1 High-pressure spray gas flow system.

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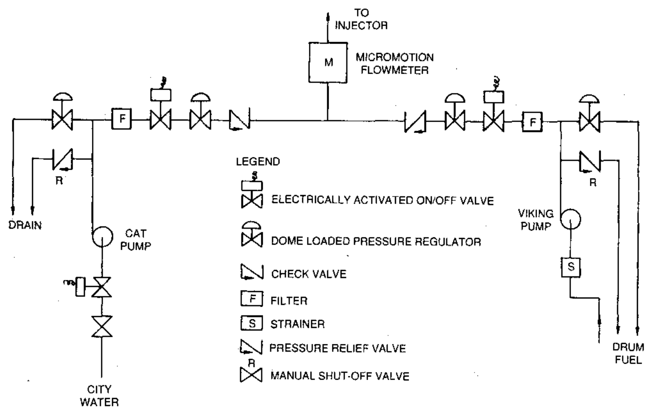


Fig. 2 High-pressure spray liquid flow system.

valve located downstream of the test section regulated test-section pressure. Test-section pressures of up to 2070 kPa were achieved. The gas supply for the fuel nozzle/swirler was driven by the pressure drop produced by a perforated plate upstream of the test section, and regulated by a remotely actuated control valve. High-pressure quench water was injected immediately upstream of the backpressure valve when operating at high-temperature conditions in order to prevent overheating of the valve seals. Excess liquid and vapor fuel was removed from the exhaust gas flow using a scrubber system.

The high-pressure spray facility was designed so that a variety of liquids could be delivered to the fuel nozzle. A schematic diagram of the liquid flow circuit is shown in Fig. 2. It consisted of parallel high-pressure water or fuel supplies, each containing a pump, backpressure regulator, and flow-control regulator. A mass flowmeter was in the common delivery line to the fuel nozzle. The fuel-supply system drew either from a 10,500 kPa Jet-A system or from a fuel drum. Liquid flow rates in excess of 500 kg/h at 4000 kPa have been achieved. Fuel nozzle supply pressure was monitored using a pressure transducer.

Spray Test Section

The test section for the high-pressure spray facility was designed to operate at pressures of up to 2175 kPa at temperatures up to 810°K. The test section was cylindrical, 10 in. in diameter, with four quartz windows at the twelve, three, six and nine o'clock positions (Fig. 3). The windows were 7.6 × 12.7 × 2.54 cm thick, and were designed to meet the same ratings as the test-section housing. Air was blown over the inner surface of each window from a slot positioned along the upstream end of the window mount. This air was used to keep droplets from the spray from fouling the window and degrading any optical measurements. Typically, a strobe illuminated the spray through the bottom window, with a video camera positioned to record through the top window. A television monitor and videocassette recorder were used to monitor and record the image of the spray. The strobe frequency was synchronized with the video scanning rate to enhance the image quality.

In most gas turbine engines, the fuel nozzle is mounted in an air swirler that assists the fuel atomization and distribution processes. Because the airflow through these swirlers is believed to have a large effect on atomization and patternation, it was desirable to have a facility that accepted the nozzle/swirler combination, and provided a controlled airflow independently of the test-section airflow. Figure 4 schematically represents the manner in which fuel nozzles were mounted. A nozzle/swirler combination was mounted at the end of a cylindrical duct located inside the test section on its centerline. The nozzle/swirler airflow orginated upstream of a perforated plate located at the test section inlet. In this manner, heated

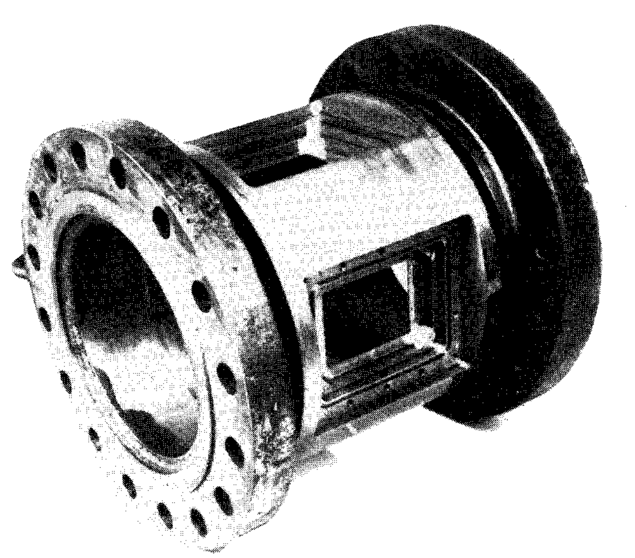


Fig. 3 High-pressure spray test section.

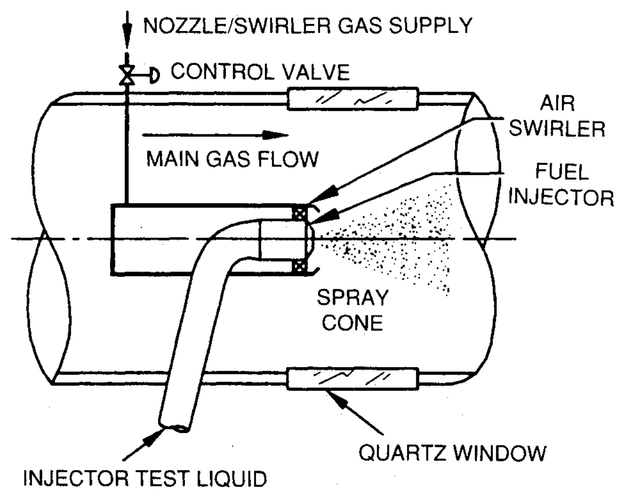


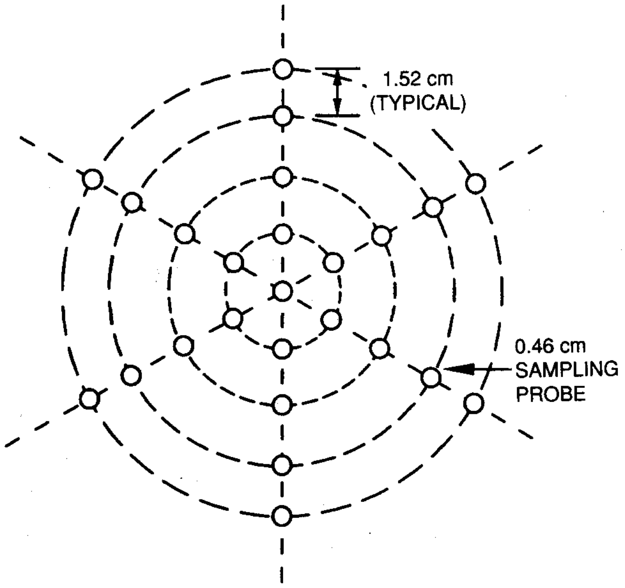
Fig. 4 High-pressure spray nozzle/swirler mounting.

airflow was supplied to both the nozzle/swirler assembly and the test section. The nozzle/swirler air was regulated by a remotely-controlled valve. The differential pressure across the nozzle/swirler combination was measured; the nozzle/swirler airflow was set by matching the pressure difference between the internal duct and the test section to the test condition. The nozzle was rigidly mounted to provide the proper engagement in the swirler that was tack welded to the duct end.

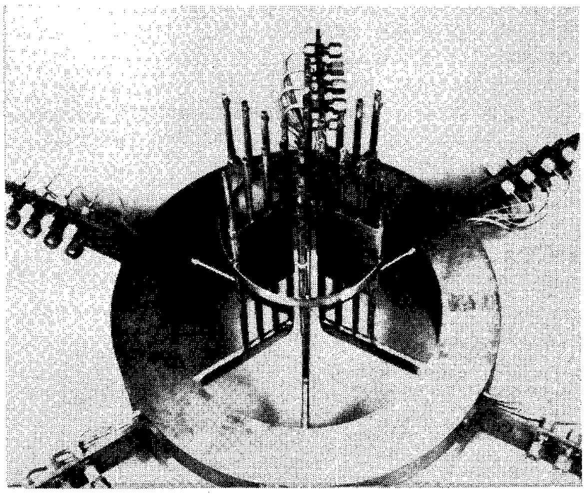
Patternation System

The high-pressure spray facility was equipped with a fixed-position, 25-point patternation system, shown in Fig. 5. Probes were arranged in a wagon-wheel fashion with six radial spokes and a center probe. Each spoke contained four probes at equal radial separations of 1.52 cm. The diameter of the rake was 12.2 cm. Each probe had an inner diameter of 0.46 cm and contained an internal pressure tap to sense the static pressure inside the probe. Liquid collected by a probe was bypassed to a drain until the sampling process began. At that point, the probes fed liquid collectors, each of which was equipped with a capacitive liquid-level sensor. The transfer lines between the probes and the collectors passed through a cooler/condenser in order to cool and condense any vaporized fuel that was collected. Figure 6 depicts the control/collection system for each probe.

An Apple IIe computer was dedicated to the task of controlling the patternation process. Isokinetic sampling was



a) PATTERNATION RAKE AND MOUNTING



b) HIGH PRESSURE PATTERNATION RAKE

Fig. 5 High-pressure patternation rake.

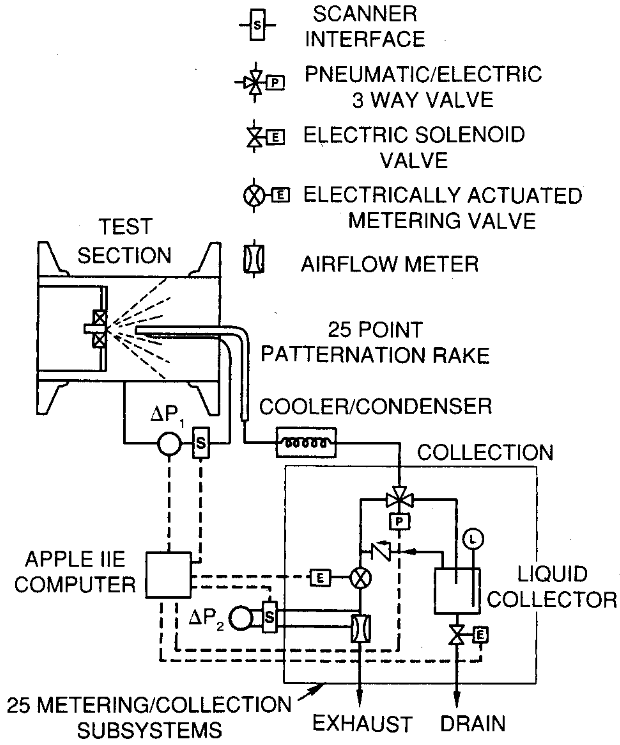
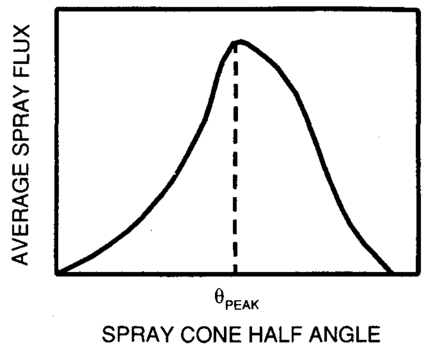


Fig. 6 High-pressure patternation system.



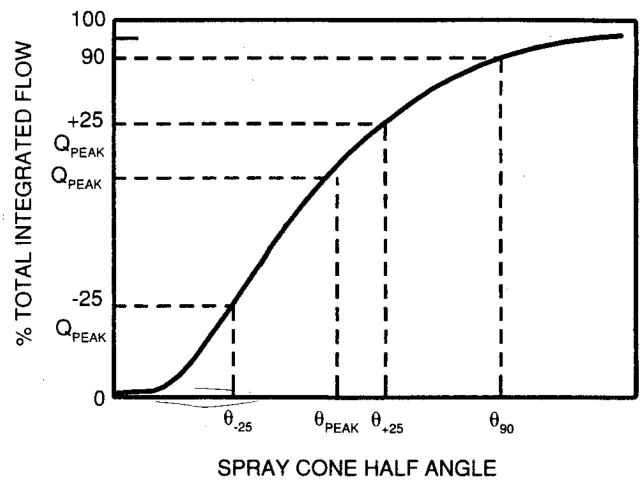


Fig. 7 Definition of spray cone angles.

achieved by nulling the differential pressure between each probe line and the test section. This was accomplished by using the computer to monitor the output of a pressure scanner that sensed the differential pressure, and commanded metering valves in each probe line to open or close. The total time required to adjust every sampling line, if done in sequence, would exceed the test time. Instead, a multitasking control strategy was used. First, the response of each probe to a metering valve change (i.e., change in differential pressure per unit time of valve actuation) was stored in a calibration table. These data provided information on the duration a valve should open or close at a set rate in order to adjust the differential pressure. Then, during operation, the computer drove the scanner to a particular port, sensed the deviation from null pressure, and initiated metering valve action by closing a relay. The computer immediately stepped to another port and commanded a second metering valve. When at a second (or subsequent) port, the computer monitored the relay condition for the original port, and turned it off once the calculated driving time was achieved. This process continued in sequence, allowing all metering valves to be adjusting simultaneously. All air pressure lines were purged frequently to prevent liquid fuel from contaminating the pressure scanner and transducers. The computer monitored the level of liquid in each of the collectors, as measured by capacitive sensors. Other data relevant to the experiment were also recorded and monitored using the computer. These included temperatures, fuel mass flow rate, airflow rate, test-section pressure, and fuel pressure. Calibration information for all of the instrumentation was stored in the computer memory, allowing real-time output in engineering units.

The sampling process began once the test conditions were achieved. The computer actuated a valve, allowing liquid to fill the liquid collectors instead of being bypassed to the drain. The computer sequentially stepped through all 25 control/collection subsystems. The metering valves were commanded, on each scan, to open or close for the time needed to balance the control pressure differential to within 0.5 kPa. Sampling continued for a preset time or until any liquid collector filled to a predetermined level. Sampling was stopped then, bypassing liquid back to the drain. The computer then calculated the volume of liquid collected from the difference in liquid levels before and after sampling. A typical computer output showed volume of collected liquid, airflow and control pressure for each of the probes and a simple bar chart indication of the spray pattern. Data were also stored on a floppy diskette. The liquid collectors were drained in preparation for the next run.

Data Reduction

Patternation data were processed on an Apollo DN460 series computer. Spray mass flux contours were plotted, as well as averaged azimuthal and radial mass flux distributions. Spray angles were computed which represented the angle at which the maximum mass flux occurred, the angle within which 90% of the total mass flux occurs, and the angles that envelop the band of ±25% of the total mass flux from the maximum mass flux angle, as shown in Fig. 7. The ±25% values indicate the thickness of the spray sheet and the spray cone solidity. The patternation data were integrated over the area of the rake, yielding an overall integrated flow rate. This was compared to the input flow rate measured by the mass flow meter. Circumferential uniformity was indicated by comparing the percentage of flow contained in a local 45-deg sector to the ideal average sector value of 12.5%. Typical processed patternation data is shown in Fig. 8, which contains a spray mass flux contour plot, a plot reflecting the percentage of spray contained within a sector at any circumferential angle, and a perspective surface plot of spray distribution. A more detailed description of data-reduction techniques is given in Ref. 4.

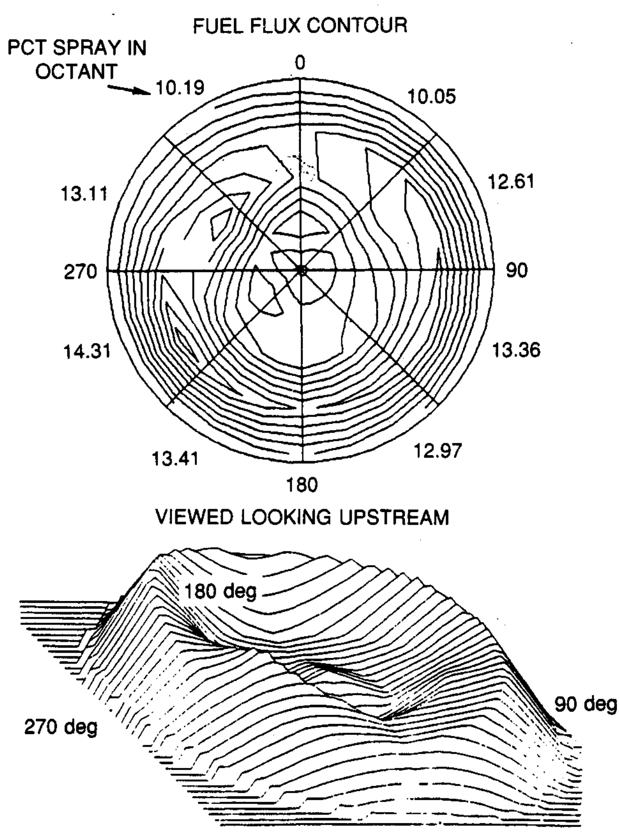


Fig. 8 Typical processed high-pressure patternation data.

Data

High-pressure patternation data have been acquired for several types of fuel nozzles.[5] These include pressure atomizers, airblast atomizers, and prefilming airblast atomizers. Many of these in-service nozzles produce nonuniform sprays. As an example of the importance of studying nonideal sprays, it is useful to consider the spray produced by an in-service dual-orifice pressure atomizer (Fig. 9). The injector was of typical scale for an aircraft gas turbine, being sized to allow 500 kg/h of fuel flow at high-power conditions. This injector employed a small airflow (0.2% of the total combustor airflow) directed radially inward (no swirl) across the nozzle face in order to keep fuel from wetting the injector and causing performance-impeding carbon deposits.

Until recently, most spray testing has been done at ambient temperature and atmospheric pressure. This has always required some type of scaling procedure to model the actual operating conditions of the injector. The parameters most often scaled are air pressure, air temperature, nozzle/swirler air velocity, air density, nozzle/swirler air pressure drop, fuel-mass flow rate, and air/fuel momentum ratio. If different fuels are to be tested, fuel viscosity, surface tension, and density also become relevant.

In order to investigate the effects of different scaling procedures on spray behavior, different parametric variations on

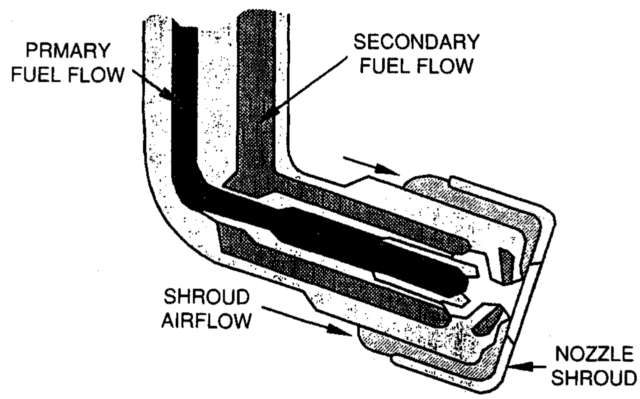


Fig. 9 Dual-orifice pressure atomizer with nozzle shroud airflow.

Table 1 High-pressure spray test conditions

Test condition	P_{gas}, kPa	T_{gas}, °K	ΔP_{gas}, kPa	Gas density, kg/m³	Gas velocity, m/s	Liquid flow, kg/h
A-1	475	560	19.1	3.0	115	50,120,180,270
A-2	250	560	10.1	1.6	115	50,120,180,270
A-3	250	300	10.1	3.0	85	50,120,180,270
A-4	475	560	0.0	3.0	0	50,120,180,270
B-1	1375	660	50.9	7.2	120	50,120,180,270
B-2	625	660	22.5	3.2	120	50,120,180,270
B-3	625	300	22.5	7.2	80	50,120,180,270
B-4	1375	660	0.0	7.2	0	50,120,180,270

Table 2 Comparison of preserved properties for parametric scaling

Condition	P_{gas}	T_{gas}	ΔP_{gas}	$\dot{m}_{gas}$	Gas density	Gas velocity	Gas momentum
1	1	1	1	1	1	1	1
2	Low	1	Low	Low	Low	1	Low
3	Low	Low	1	1	1	1	1
4	1	1	Low	Low	1	Low	Low

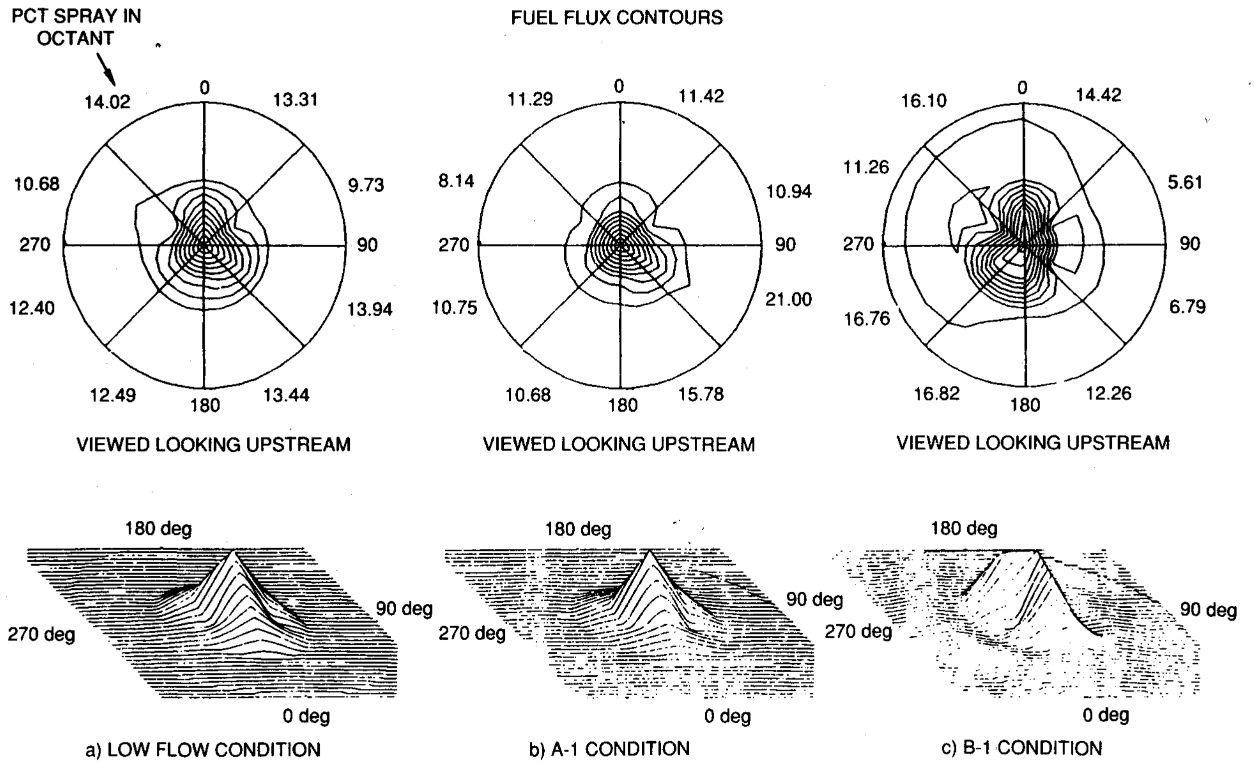


Fig. 10 High-pressure patternation reveals collapsed spray.

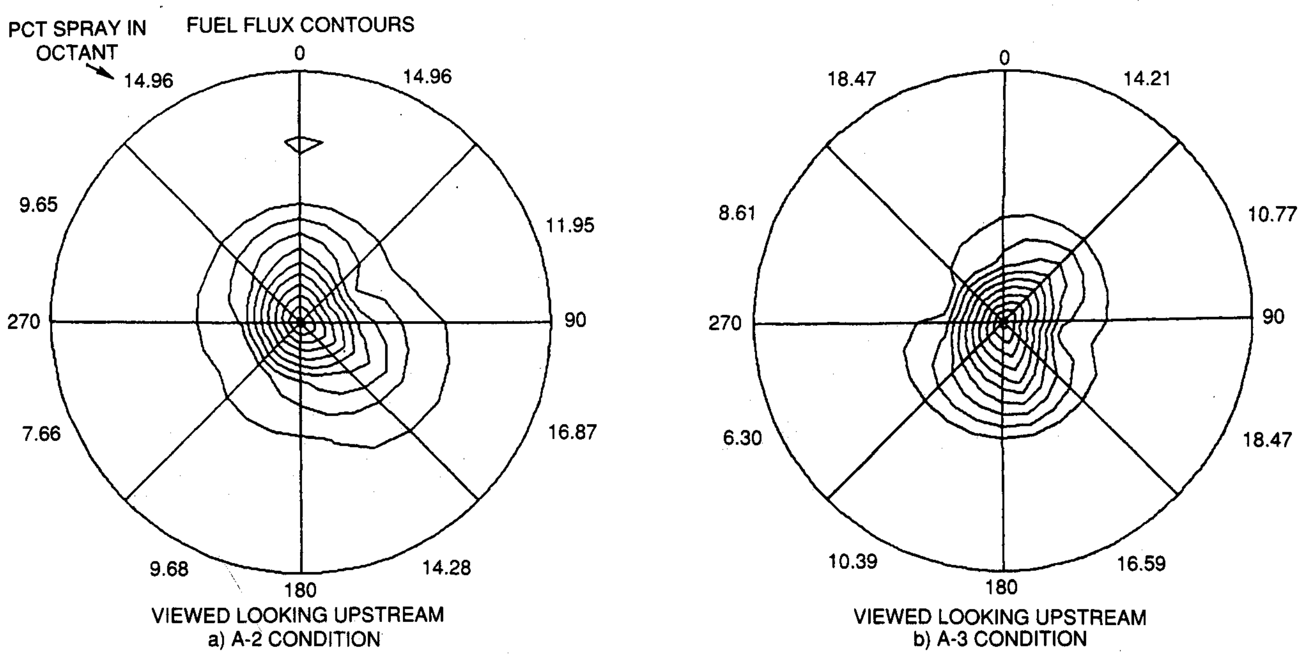


Fig. 11 Parametric variations 2 and 3 do not change spray pattern.

the nominal conditions were performed. Table 1 lists these test-condition variations that were calculated as follows:

Condition 1

Nominal conditions from engine.

Condition 2

Variation of air pressure, holding air temperature, nozzle/swirler air velocity, and nozzle/swirler pressure drop percentage ($\Delta P/P$) constant.

Condition 3

Variation of air pressure and temperature, holding air density, nozzle/swirler air velocity, nozzle/swirler pressure drop (ΔP), and air momentum constant. These tests were performed at ambient temperature.

Condition 4

Variation of nozzle/swirler air velocity, holding air pressure, and temperature constant.

Table 2 shows the variation of condition with respect to the nominal condition. The number "1" represents a variable held constant with respect to the nominal (condition 1) value, and variations are indicated by "high" or "low."

The injector produced a collapsed spray cone at all three nominal test conditions (condition 1). The spray contours for

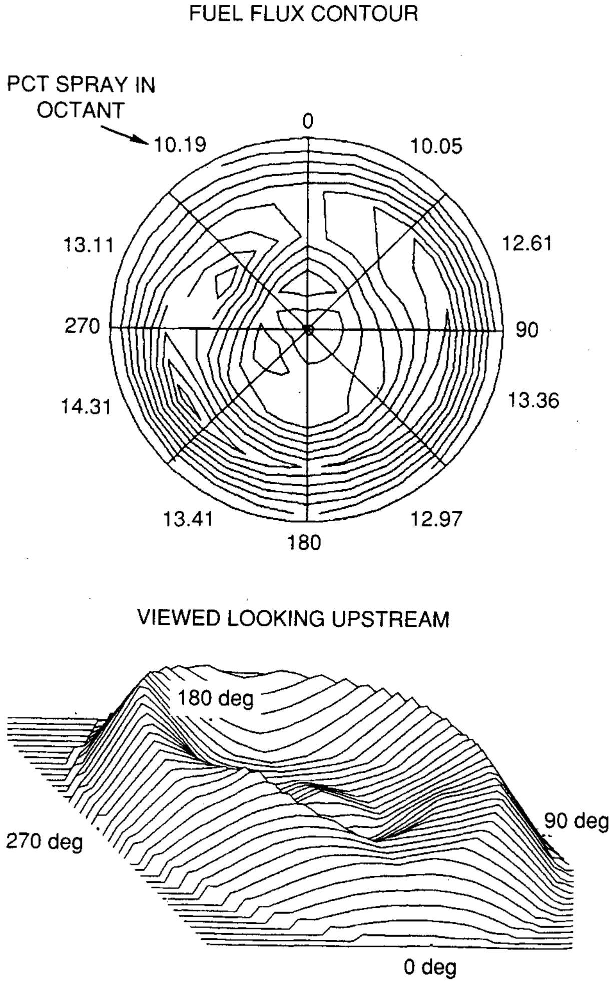


Fig. 12 Spray cone opens when anticarbon air is decreased.

these three tests with a water spray are shown in Fig. 10, illustrating the magnitude of this effect. The spray collapsed into a single, coarse jet for all of the liquids tested. This phenomenon was also present at two of the parametric variations on the test conditions (2 and 3). Figure 11 shows sample results for these two variations. For these tests with full nozzle airflow, the spray always exhibited a peak spray angle of 0 degrees. The extent of the spray cone is indicated by an angle of 38 degrees enveloping 90% of the spray.

At the other parametric variation, number 4, where airflow through the nozzle/swirler is decreased, the spray cone opened up into a hollow cone. The results shown in Fig. 12 show the spray to be a nearly axisymmetric hollow cone at variation number 4. Here the spray angle was 42 degrees, with 50% of the spray lying between 35 and 47 degrees. These values indicate a thin, hollow-cone spray. Photographs of both the collapsed spray and the hollow cone spray are shown in Fig. 13, along with corresponding patternation results.

This result is consistent with results obtained at ambient pressure conditions. The large effect of the nozzle airflow on the spray pattern may be seen in Fig. 14. The spray cone was collapsed and six peaks were observed in the spray pattern. These were traced back to the six struts used to hold the air cap. The streaks were not detected at high pressure due to the further extent of the cone collapse and the relative coarseness of the patternator.

No effect of fuel type on spray patternation was observed. The collapsing of the spray cone by the nozzle airflow completely dominated all other effects. No variations were seen between patternations with water, JP-8, JP-4, DF2, and a high-density fuel.

The pronounced effect of such a small nozzle airflow was due to the large inward radial air velocity created by the air cap. The nozzle airflow was not swirled so that the typical benefits of swirl for increasing spray cone angle were lost. Although the air cap flow was originally introduced to prevent mist from wetting the atomizer face and subsequently forming carbon deposits that impede injector performance, the flow caused the collapse of the spray and forced undesirably fuel-

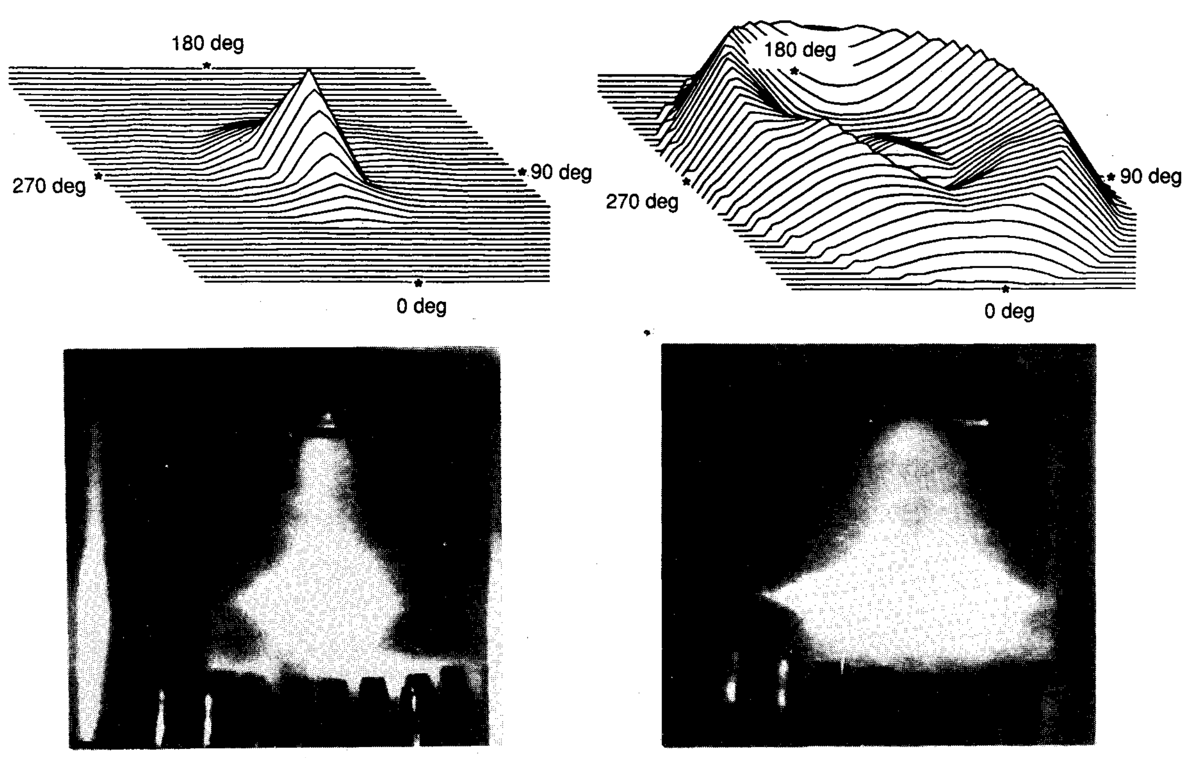


Fig. 13 Video image verification of high-pressure spray patternation results.

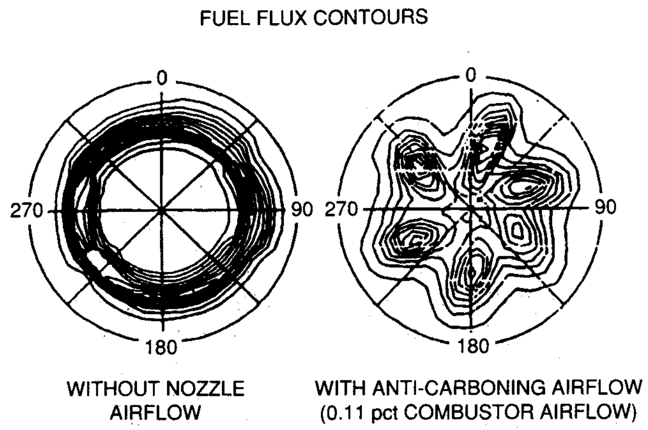


Fig. 14 Effects of anticarbon air on ambient spray pattern.

rich regions in the combustor. With this knowledge, it was not surprising that very high smoke numbers were common for this injector.

Conclusions

Patternation data have been acquired for a dual-orifice pressure atomizer at conditions identical to those experienced in a gas turbine combustor. This in-service nozzle was operated at pressures up to 1380 kPa, temperatures of up to 640°K, and fuel flow rates of up to 500 kg/h.

The data show that the "small" amount of airflow used to keep carbon deposits from forming on the injector face caused the spray cone to collapse at combustor operating points. As the nozzle airflow was reduced, the spray opened into a hollow cone. These results are indicative of the need to study non-ideal, in-service nozzles at real conditions, employing all airflows associated with the actual operation of the device.

Acknowledgments

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