High-Resolution Patternator for the Characterization of Fuel Sprays

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The features of a high-resolution patternation system used for measuring the spatial distribution of mass flux delivered by gas turbine engine fuel injectors having large-volume flows are described. The patternation system is based on the use of extractive probing by means of a multipoint sampling rake. Testing is conducted under ambient pressure conditions. Results of tests conducted to verify the capabilities of the system are presented. Applications of the system to establish the impact of injector aerodynamic and hydraulic design features on spray uniformity are discussed.

Nomenclature

A_c	= cross-sectional area of collection cylinder
A_p	= cross-sectional area of probe tip
A_r	= area of circle circumscribing the patternation rake
d	= distance between injector face and sampling plane
h	= collected sample column height
min/max	= ratio of patternation samples, Eq. (14)
N	= number of radial surveys
P.I.	= patternation index, Eq. (13)
q	= mass flux
r	= radius
t	= sampling time
W	= total fuel flow rate
W_i	= sector flow rate, Eq. (6)
$\hat{W}_i$	= normalized local sector flow rate, Eq. (8)
$\hat{W}_{s,45}$	= normalized 45 deg sector flow rate, Eq. (9)
w	= local flow rate
α	= spray cone angle, Eq. (12)
θ	= azimuthal position

Introduction

THE subject of this paper is the characterization of the spatial distribution of fuel produced by gas turbine fuel injectors; in particular, the characterization of the circumferential nonuniformity of fuel sprays that would be, in the absence of nonidealities, axisymmetric in nature. The term adopted by the industry for the process of establishing spray distribution is "spray patternation" and the instrumentation used is commonly referred to as a "spray patternator."[1]

Techniques for measuring the spatial distribution of spray mass flux can generally be classified according to whether the technique is optically based or utilizes extractive probing. A wide variety of optically based spray characterization techniques have been investigated and utilized in recent years, although these systems generally have not been used to obtain patternation data due to the expense associated with their operation. In principle, an optically based system would be required to gather spatially precise information on both droplet size and velocity. Velocity information is usually obtained using either of two techniques: double-pulse imaging (photography or holography) or laser Doppler anemometry. For practical purposes, the data acquired using double-pulse imaging systems must be processed using computer-based image analysis systems, although early work carried out at the University of Sheffield[2] did employ manual techniques. A current application of the automated approach is that of the Bete Fog Nozzle Inc.,[3] which employs flash lamps for droplet imaging, a video system to record the images, and a video image processing system to analyze the particle size/velocity data.

The advent of laser velocimetry (LV) for performing velocity measurements has led to a number of approaches for obtaining correlated velocity/size/spatial location data. Generally, the measurement of droplet velocity using LV is straightforward in sprays of moderate number density and it is the task of deducing droplet size from the LV signals that has received most attention. Techniques for deducing droplet size based on measurements of the signal amplitude have been reported by Yule et al.[4] and by Hess[5] and his co-workers.[6] A technique based on measurement of the phase relationship among signals received by multiple receivers has been reported by Bachalo and Houser.[7] These techniques hold the promise of providing not only the spatial distribution of mass flux, but also the detailed size/velocity correlation information required for input to aerothermal analyses. The optical techniques are limited, however, in terms of the number density of droplets that can be present before the valid date rate drops off, as well as in terms of the overall time and resources required to document a complete spray. Thus, for many practical situations involving patternation of large gas turbine engine injectors, extractive probing is the only viable approach.

Generally, extractive probing systems can be classified into two groups: 1) systems using isolated probes or an array of probes in which only a fraction of the total stream is captured and 2) systems in which the total fuel stream is captured. The former method has been used primarily to study fuel distribution in high-speed streams (e.g., ramjets).[8] In many cases, attempts are made to use isokinetic techniques to minimize probe interference effects.[9] Refinements of this technique in which both the gaseous and liquid phases of the injector fuel are captured have also been reported.[10,11] The information gathered by the use of isolated probes or small probe arrays usually provides sufficient information to document specific profiles, but it has not been widely used to generate patternation data.

Extractive probing systems that capture the entire fuel stream are most commonly used to document the spray patterns produced by fuel injectors. Generally, the airflow effects

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on spray distribution are not accounted for; typically, the spray is directed vertically downward into collection bins and the relative amounts of liquid collected by the array of bins are recorded. Such systems are easily adapted to the measurement of sprays produced by pressure atomizers, but are less easily adapted to air-blast atomizers due to the necessity of handling the high-velocity air accompaning the fuel spray. Only low-resolution spatial data are intended to be acquired, with the data typically being used for manufacturing control. Early work of this type applied to gas turbine engine injectors has been reported by Tate[12] and standard procedures for applying this type of system have recently been adopted by ASTM.[13]

As the demands on the performance of turbine engine injection systems have increased (wider flow rate range, more thorough mixing of injector air and fuel), and, as awareness of the role played by the spatial distribution of the spray has heightened, there has been increased demand to obtain higher-resolution spray patternation data in order to evaluate new injector design concepts. This article describes the design of a high-resolution patternation system based on extractive probing and provides examples of how that system is being used to evaluate the manner in which the aerodynamic and hydraulic features of air-blast nozzles influence the circumferential uniformity of sprays.

Patternation System Design Guidelines

The guidelines employed in establishing the features of the patternation system, summarized in Table 1, are based on the following considerations.

Flow Capacity

The system is to be applied to air-blast injectors capable of delivering fuel flow up to 0.16 liter/s of jet fuel. No minimum fuel flow was established, although sampling time becomes impractically long at flow rates of less than 5% of the maximum.

Test Environment

The system is designed to be operated under ambient conditions based on the belief that most departures from ideality can be detected when testing at any pressure level and the fact that the cost of operating at high pressure is prohibitive for programs directed at evaluating relatively large numbers of injectors. Because the system is used to perform tests at ambient pressure, the flow condition cannot be identical to the actual conditions experienced in a high-pressure engine. Therefore, some scaling procedures must be invoked; this is discussed in a subsequent section. The fuel temperature is currently not conditioned prior to delivery to the apparatus as it would be in a facility designed to calibrate the fuel flow schedule of a nozzle. The recorded maximum variation in temperature of Jet-A fuel as delivered from underground storage tanks has been 10°C. Test results obtained at these seasonal extremes have revealed only a minor effect of this variation on spray pattern.

Patternation Area

The cross-sectional area of the spray intercepted by the sampling system is a function of the scale of the injector, the typical spray cone angle, and the distance of the sampling plane from the injector tip. The selected value (equivalent to a 10 cm diam circle) is based on prior experience with large gas turbine engine injectors where the practice is to sample within 2–8 cm downstream of the injector tip.

Spatial Resolution

The guideline selected was to be capable of resolving variations in spray flux distribution on a length scale of 0.5 cm. This was established on the basis of the size of injectors normally dealt with, the consideration of system cost, and the time duration of a test. This specified length scale dictates the characteristic size of the sampling probe tip, the number of points per radius (10), and the azimuthal positioning requirements (a 10 deg increment in azimuth yields the required resolution at the rake midspan).

Duration of Test

The typical test duration was based on the necessity of characterizing six injectors per 8 h test shift using the nominal spatial resolution. Allowing for installation and setup, a test duration of 30 min or less is required.

Other guidelines not shown in Table 1 were that the data be processed immediately subsequent to a test period and transmitted by way of a high-speed data link to the user. This guideline, coupled with the test duration and resolution requirements, essentially dictated that computerized control, data acquisition, and data reduction systems be employed.

Patternation System Configuration

The following sections describe the patternator, the data acquisition and control system, and the instrumentation.

Patternator

The patternator includes a fuel nozzle fixturing device, the sampling rake, and the collection system. The approach used in the design of the patternator was to employ a fixed sampling rake and movable injector. The test procedure envisioned would be to position the nozzle at a given distance from the sampling rake and then to perform a series of tests at different angular positions by rotating the nozzle while holding the rake fixed. A schematic illustration of the system is given in Fig. 1.

Nozzle Fixturing

It is required that the fuel nozzle fixture permit accurate alignment of the fuel injector relative to the rake, that the noz-

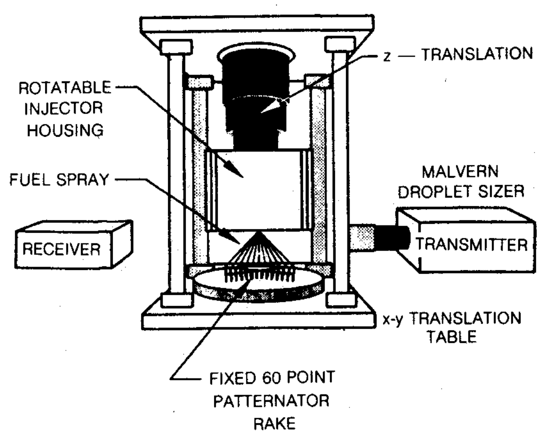


Fig. 1 Spray patternator configuration.

Table 1 Patternation system design guidelines

Flow capacity
Maximum fuel flow rate: 450 kg/h (1000 lb/h)
Maximum airside pressure drop: 240 Torr (130 mm H_2O)
Test environment
Pressure: ambient
Fuel temperature: ambient
Air temperature: ambient
Patternation area
Circular diameter = 10.2 cm
Spatial resolution
Radial: 0.5 cm—10 probes/radius
Circumferential: 10 deg increment typical, 5 deg min required
Test duration: 30 min typical

zle installation time be minimal, and that provisions be made for delivering fuel and air to the nozzle. Once the fuel nozzle is properly aligned with the patternator rake, the only motion required or allowed is rotation of the nozzle about the axis of symmetry of the nozzle barrel. The approach used is to perform manually all of the alignment adjustments except rotation, which is accomplished by the automated control system.

The fuel injector is mounted in an enclosure that serves as both the nozzle fixture and air plenum; the fuel is sprayed vertically downward. A photo of the enclosure with the access cover removed is given in Fig. 2. The nozzle is affixed to a detachable mounting plate such that the face of the injector protrudes through an opening in the base plate and extends 2.5 mm beyond the bottom surface of the plate. The opening is fitted with an O-ring that seals and centers the injector. Fuel is supplied to the injector by means of flexible 6.35 mm i.d. hose. When the access cover is secured, the nozzle enclosure forms a sealed air plenum. Air is delivered to the plenum from a regulated supply through a fitting at the top of the enclosure utilizing another flexible hose of 16 mm i.d. The diameter of the plenum is 45.7 cm, which is sufficient to accommodate most injectors in use in large gas turbine engines.

The plenum is electromechanically rotated using a precision rotary stage and stepping motor. Rotation occurs about the centerline of the barrel of the injector. The injector may be electromechanically translated vertically over a 15 cm span to permit the acquisition of patternation data at selected downstream planes. Two pairs of linear translation stages permit precise manual X-Y displacement of the plenum to facilitate centering of the injector relative to the array of spray sampling probes. Displacement up to ± 5 cm in the X-Y direction is possible for special tests. The plenum is supported from above by a triangle of adjustable pivot points so that the axes of the injector and sampling probes can be precisely aligned. Alignment is checked by inserting a fixture into the injector barrel and observing the wobble of an indexing pin relative to the center of the fixed probe as the injector is rotated.

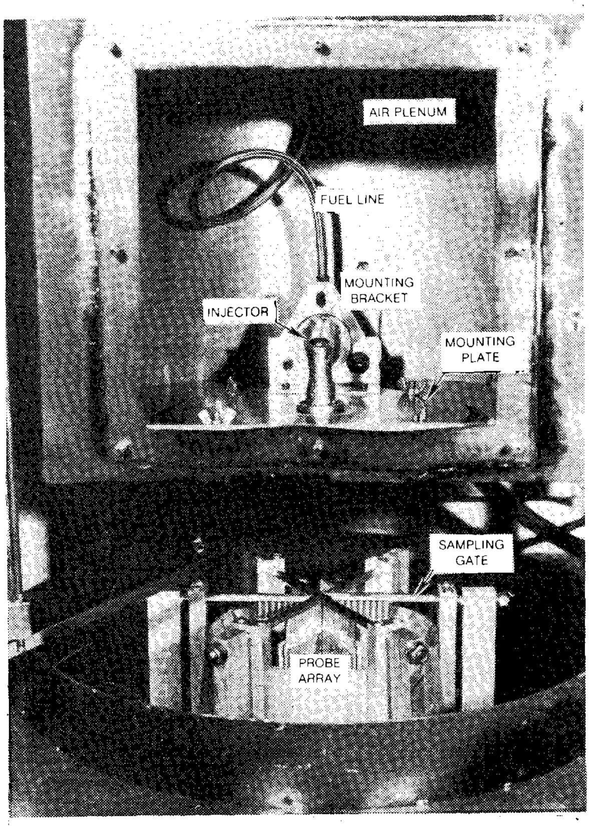


Fig. 2 Fuel nozzle fixturing arrangement.

Spray Sampling Probes

There are 60 sampling probes arranged in linear arrays of 10 each radiating from the axis. The spray sampling area is thereby divided into six equal sectors (see Fig. 3). The probes are squared at the inlet and have been chamfered outward so that the line of contact between probes forms a knife edge. The inlet area of the individual probes is roughly equivalent to that of a circular tube having a diameter of 5 mm.

Each of the six probe arrays is shielded from the spray by an inverted trough-shaped cover plate that acts as a closed sampling gate except during actual collection of the sample. At the start of sampling, the six sample gates are simultaneously retracted by quick-acting, air-actuated pistons. Upon completion of sampling, the probes are simultaneously covered by the reverse action of the pistons. Use of the sampling gates permit adjustment of the fuel and air flow rates prior to the beginning of sample collection and prevents any inaccuracies caused by the fuel draining from the injector into the probes after the sampling time has expired.

Due to gravity, the fuel entering each sampling probe passes through attached tubing to 1 of 60 individual collection cylinders. For ease of servicing, these cylinders are located outside of the main spray chamber. Each transfer tube passes through a tight-fitting hole before reaching the collection cylinders, such that fuel impinging on the outside of the transfer tube cannot enter the collection chamber. The transfer tube ends 2.5 cm below the top edge of the open collection cylinder, such that the liquid sample drops readily into the cylinder and the accompanying airflow is exhausted to the main spray chamber. It should be noted that the main spray chamber is maintained at a slight negative pressure. Fuel enters the sampling probes by virtue of the momentum of the droplets; no attempt is made to sample isokinetically.

Fuel Collection Cylinders

The configuration of an individual collection cylinder is illustrated in Fig. 4. It comprises four elements: the cylinder proper, the feed tube from the sampling probe, the pressure-sensing tube, and the fuel ejector. The collection cylinder is fabricated from stainless steel tubing having an inner diameter of 22 mm. The volume of the sample collected is determined from the height of the liquid column (established by the pressure exerted thereby) and the cross-sectional area within the cylinder. The net area is equal to the cylinder area less the area occupied by the pressure-sensing and fuel-ejector tubes and is equal to 3.3 cm^2. The pressure exerted by a collected sample of jet fuel having a specific gravity of 0.82 can be calculated to be 7 Torr per liter. Calibrations conducted by measuring the pressure exerted by 25 cm^3 of fuel injected into each cylinder by use of a syringe show the average deviation between the measured and calculated data to be less than 1%.

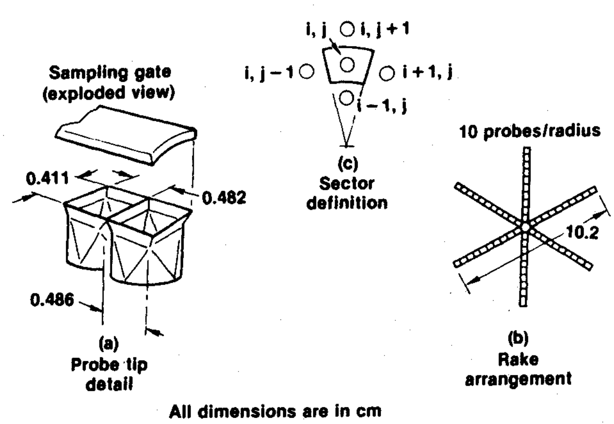


Fig. 3 Patternator probe configuration.

The pressure-sensing tube traps a volume of nitrogen under a head exerted by the liquid. The nitrogen transmits this pressure to a dedicated transducer.

After each sampling cycle, the fuel is removed from the collection cylinder by means of an air-driven fuel ejector. The depth to which the ejector tube is immersed in the cylinder establishes the level of the fuel prior to the start of sampling. This level is set at 4.5 cm above the tip of the pressure-sensing tube so that a positive head exists at the start of the test. The spray of fuel and air from the ejector discharge is directed back into the main enclosure for disposal. The ejector action is used, rather than the action of a positive pressure purge, in order to avoid overpressuring the sensitive transducers.

Spray Chamber

The main spray chamber consists of a 1.2×1.2×1.2 m enclosure with appropriate baffles of metal screens and packing so that the fuel and air from the nozzle and the ejector may flow freely while the fuel and air are separated. The enclosure is kept at a slight negative pressure (1.0 Torr) by an induced draft fan exhaust system. A transfer pump is used to periodically remove the collected fuel from the enclosure for disposal. The chamber is equipped with a sensor and a safety system such that in case of fire a CO_2 extinguishing system is activated and rig shutdown is initiated.

Data Acquisition and Control System

The data acquisition and control system consists of a host computer and peripherals, the instrumentation, and various drive components.

Host Computer

The requirements of the host computer are modest in terms of data rate, memory, and mass storage; therefore, a microcomputer provides the most cost-effective approach. An Apple IIe equipped with Interactive Microwave ADALAB analog-digital (A/D) cards is employed. Details of the interfacing between the computer and patternation system can be found in Ref. 14.

Instrumentation

The instrumentation consists of the pressure transducers employed for the measurement of the volume of liquid accumulated in the collection cylinders, the angular positioning equipment, and those standard components used for the measurement of the fuel and airflows.

Two techniques were considered for the measurement of the volume of the collected fuel sample: measurement of the pressure exerted by the column of collected fuel and measurement by use of commercial liquid-level-sensors that operate on the basis of the change in capacitance, which occurs as liquid fills the space between the charged plates. Both methods for measurement of the sample volume are in use in our laboratory and, for this application, neither approach offered a clear-cut cost advantage. The pressure-sensing system was chosen primarily because of the compactness of the system and the ease of computer interfacing offered by the particular unit selected. Two ZOC-12 multichannel pressure-sensing modules produced by Scanivalve Corporation are used for the measurement of the pressure exerted by the collected sample. Each module contains 32 individual transducers such that a dedicated transducer is available for each of the 60 collection cylinders, with four spares remaining. Further information on the pressure-sensing system is available in Ref. 14.

The angular position is established by a Daedal model PC 401 single-axis motor controller that activates a stepper-motor-driven rotary stage. The resolution employed is 0.02 deg/step; the drive speed employed is 400 steps/s.

Fuel is delivered by the facility supply system at pressures to 10 MPa. The flow is split such that duplex nozzles with independently controlled primary and secondary fuel passages may be tested. Manually operated regulators are used to establish the desired flow rates. The flow rate in the primary flow system (0–70 kg/h) is measured using a turbine meter (Cox model LF 6-0) and frequency converter (Cox 2003M). The secondary flow rate (0–400 kg/h) is measured using a vibrating U-tube type of mass flow meter (Micromotion model C-25) in combination with a digital voltmeter display.

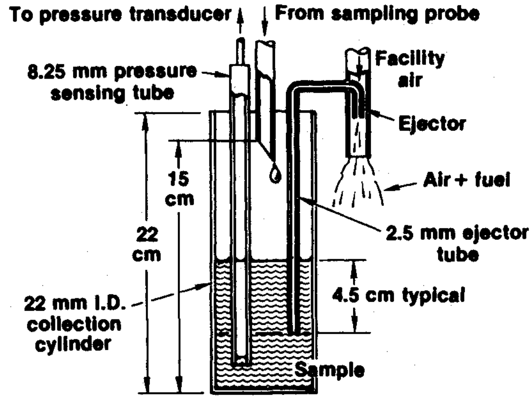


Fig. 4 Fuel collection cylinder.

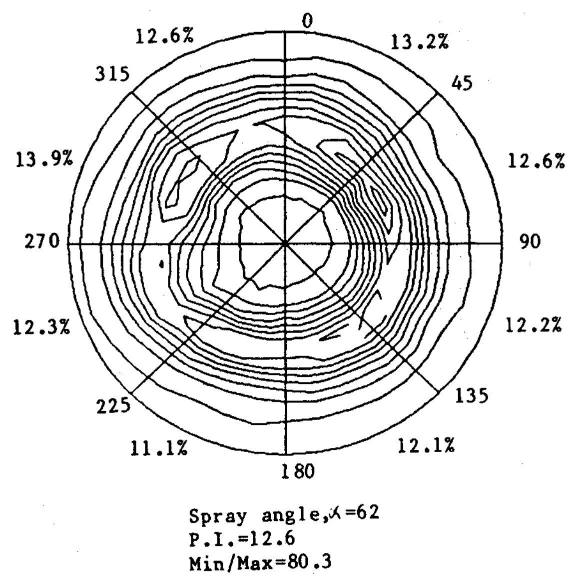


Fig. 5 Typical reduced data—contour plot.

Air is delivered by the facility air supply at pressures to 0.27 MPa and is metered using choked venturies (Fluidyne Engineering). Air temperature and pressure are measured using standard instrumentation.

All measurements relevant to flows are manually entered into the data acquisition system using the Apple keyboard.

Data Reduction

The mass flux at the sampling point is given by the relationship:

$$q = a \cdot p/t \cdot A_c/A_p \tag{1}$$

where q is the local flow per unit area, p the pressure, t the sampling time, A_c the collection cylinder cross-sectional area, A_p the probe tip area, and a a constant.

For presentation purposes, this flux is converted to a flow rate—the flow rate that would exist if the flux were uniform at the measured level across the area of the circle circumscribing

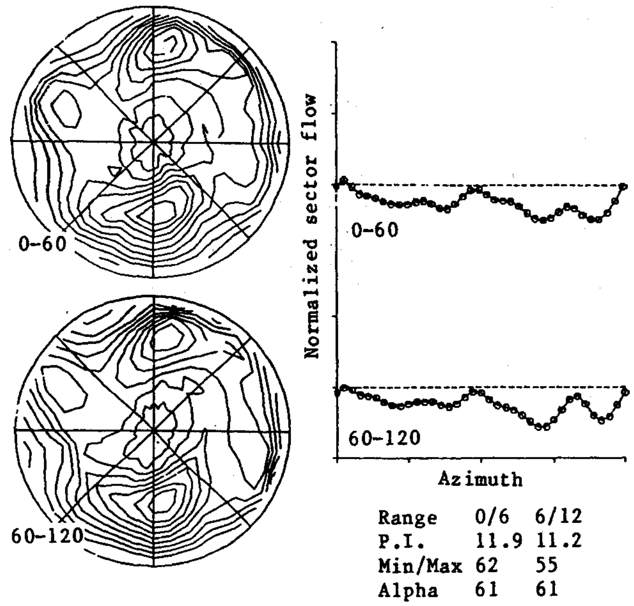


Fig. 6 Reproducibility of results, 120 deg sampling range.

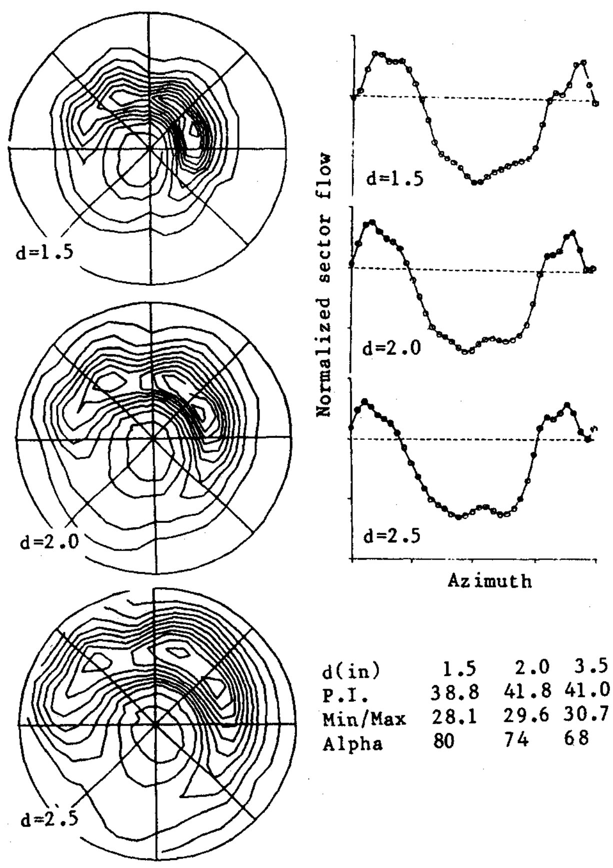


Fig. 7 Effect of sampling height.

the patternator rakes, as

$$w = q \cdot A_r \tag{2}$$

The maximum value of this quantity is referred to as the "global maximum flow rate, w_{max}" and is used as a normalization quantity,

$$\hat{w} = w/w_{max} \tag{3}$$

which, of course, is equivalent to q/q_{max}.

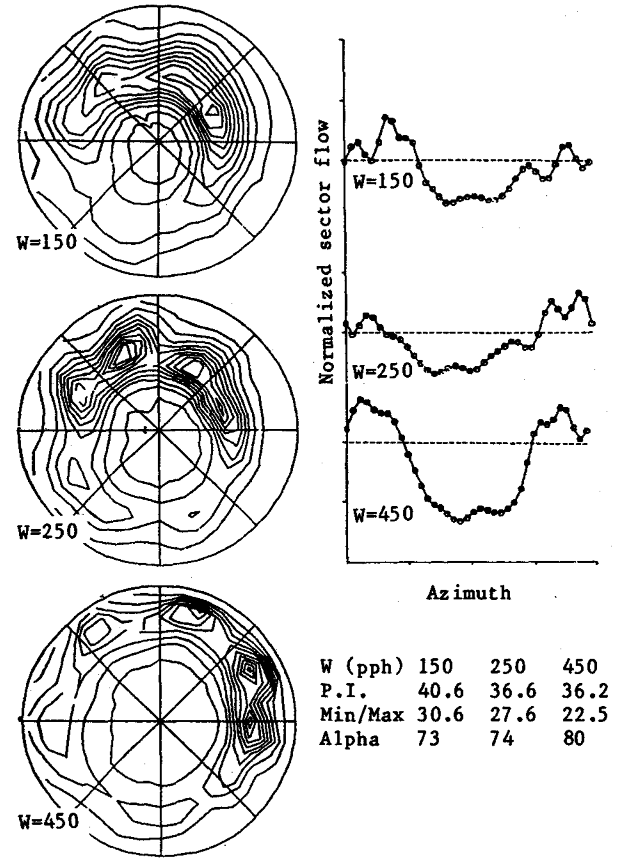


Fig. 8 Effect of fuel flow rate.

For the purpose of integrating the measured flux over the area of the patternator, the local sector element flow rate is determined from the product of the sector element area A_{ij}, and the average flux $\bar{q}_{ij}$,

$$A_{ij} = \frac{\pi}{4N}[(r_{j+1} + r_j)^2 - (r_j + r_{j-1})^2] \tag{4}$$

$$\bar{q}_{i,j} = \tfrac{1}{2}[q_{i,j} + \tfrac{1}{2}(q_{i-1,j} + q_{i+1,j})] \tag{5}$$

where r_j is the radial location of the jth probe, N the total number of radial surveys, and the index notation shown in Fig. 3c is used.

The local sector flow rate is defined as

$$W_i = \sum_{j=1}^{10} \bar{q}_{i,j} \cdot A_{i,j} \tag{6}$$

The total flow rate is

$$W = \sum_{i=1}^{N} W_i \tag{7}$$

A normalized local sector flow rate is obtained by dividing the local value by the total flow per unit sector,

$$\hat{W}_i = W_i/(W/N) \tag{8}$$

The subscript s, being mnemonic for "sector" is preferred; thus, $\hat{W}_s = \hat{W}_i$. In a similar manner, sector flow rates (both normalized and unnormalized) may be obtained for sectors of any angular size by carrying out summations over appropriate ranges. The data obtained by the rake patternator can then be used to generate information corresponding to that produced by a bin-type system. In current applications, it is practice to calculate a normalized 45 deg sector flow expressed in percentage form as

$$\hat{W}_{s,45} = \sum_{i=i_1}^{n} \hat{W}_i \times 100 \tag{9}$$

where i_1 designates the radial traverse position at the start of sector s and n is the number of traverses in a 45 deg sector.

Parameters describing the radial distribution patterns are calculated in a similar manner. The local annular flow rate is defined as

$$W_j = \sum_{i=1}^{N} q_{i,j} \cdot A_{ij} \tag{10}$$

and is normalized

$$\hat{W}_j = \frac{\hat{W}_j}{W/10} \tag{11}$$

with the mnenomic subscript r being substituted: $\hat{W}_r \equiv \hat{W}_j$.

The fuel spray angle produced by the injector can be defined on the basis of that cone extending from the injector face to the measurement plane that intercepts a specified fraction of the total flow rate. The spray angle is determined using the expression

$$\alpha = 2 \cdot \tan^{-1}\left(\frac{r_f - r_b}{d}\right) \tag{12}$$

where r_f is the radius at which the intergrated flow rate equals a specified fraction of the total flow rates (a typical value is 0.9), r_b the radius of the filmer barrel, and d the distance between the sampling plane and the injector face.

Data reduction is carried out using an Apollo DN460 computer in order to take advantage of the graphics capability of that system. Black-and-white hard copy is generated using a Versatec-V80 printer.

A contour plot (Fig. 5) is used for a comprehensive quantitative presentation of the data. Contour levels may be either prespecified or based upon the range of measured levels. Shown at the perimeter of the plot are the percentages of the total flow found in each octant $W_{s,45}$. The classical tests of pattern uniformity are the patternation index (P.I.) and the min/max ratio. The P.I. for an eight-bin patternator is calculated as

$$\text{P.I.} = \sum_{s=1}^{8} | W_{s,45} - 12.5 | \tag{13}$$

The min/max ratio is determined from the flow rates in the sectors passing the lowest and highest flows as

$$\text{min/max} = W_{s,45,\text{min}} / W_{s,45,\text{max}} \tag{14}$$

The min/max ratio is often used as an acceptance criterion for a nozzle during quality control testing.

Selection of Test Conditions

A selection must be made of the fuel flow rate and air side pressure drop to be used in the patternation of sprays at ambient pressure. It is not possible to simultaneously preserve all of the significant parameters corresponding to engine operation when scaling from high pressure to ambient pressure conditions. Generally, this particular apparatus is applied to the documentation of fuel nozzle performance at high-flow conditions (a horizontally oriented patternator is most useful for low-flow conditions). The procedure used at our laboratory for the simulation of sprays produced under high-power engine conditions is as follows.

The air side pressure drop is selected so as to produce the same air velocity as is generated by the swirler at engine operating conditions. This velocity is determined from the scheduled compressor discharge pressure and temperature and the combustor liner pressure loss. A typical value is 125 m/s. The corresponding pressure drop required at ambient condition is 65 Torr.

The fuel flow is established by specifying that the air-to-fuel momentum ratio is the same as that at engine conditions. A typical ratio is 30:1. The parameter that is not preserved in this process is the fuel flow rate. Therefore, for selected injectors it is the practice to vary the fuel flow rate upward by a factor of two or three in selected tests.

System Qualification Tests

Several tests have been carried out to establish that the patternator can be used to accurately assess the spatial distribution of fuel sprays. The results of these tests are described below. Most of these tests were conducted using fuel nozzles that produced highly asymetric fuel patterns such that changes in the distinctive patterns due to altered test procedures could be easily discerned. All tests were conducted using Jet-A fuel.

A typical repeatability test is illustrated by the results shown in Fig. 6. This test was conducted by rotating a given injector through a 120 deg azimuthal range rather than the 60 deg range typically used. The upper contour map shown in the figure used data acquired in the first 60 deg range of variation, while the lower map used the remaining data. This example tests not only the ability to produce repeatable results, but several other features of the patternation system as well. At any given azimuthal location, a different leg of the rake and of the collection system was used to collect and measure the sample in the two ranges. If a probe, collection cylinder, or transducer were out of specification, the bias introduced thereby would appear in a different sector of the contour plot and would be apparent. Also, the average level of the fluid in the collection cylinder was different in the two portions of this run. Biases due to nonlinear transducer behavior, to a changed degree of spray carryover, or to leakage associated with the liquid column height should therefore be observed. Finally, the precision of the alignment of the nozzle with the rake centerline is tested.

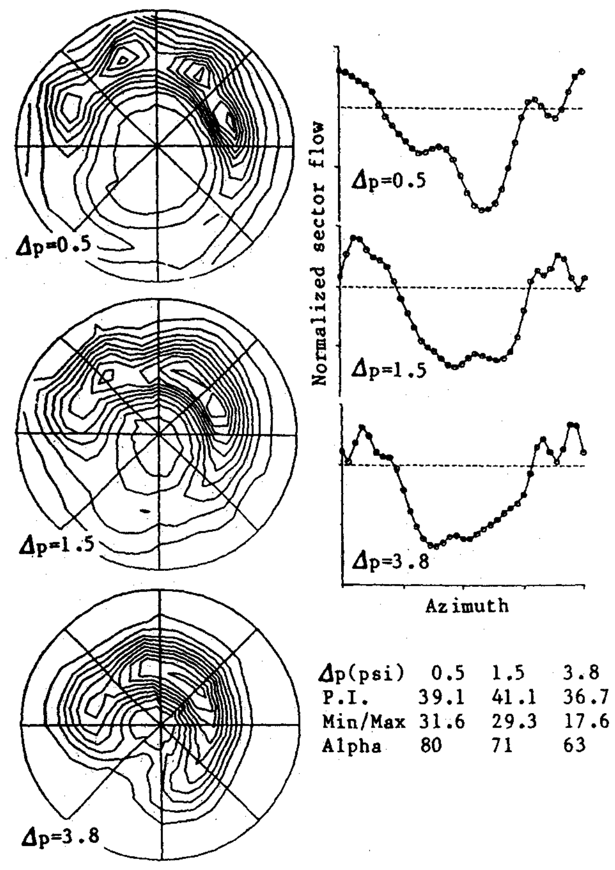
Good reproducibility is observed in these results, with the exception of the higher local maximum in the upper left quadrant in the lower map in Fig. 6. This discrepancy was traced to the bistable airflow pattern generated due to a skewing of the injector air cap during assembly. This skewing resulted in an occasional shift in the swirler air discharge pattern when the flow of air and fuel were initiated at the start of a survey. The change in airflow pattern is suspected to be associated with an unstable flow separation phenomenon.

Measurement Plane Location

Shown in Fig. 7 are patternation results for measurements performed 3.8, 5.1, and 9.9 cm from nozzle tip. The contour plots show the expected results—the patterns are similar, but expand in scale with increasing distance. The tabulated patternation parameters show only a slight variation. The calculated spray angle decreases with increasing distance, which reflects the expected spray envelope for airblast nozzles.

Fuel Flow Rate

Tests were performed to evaluate the effect of increasing flow rate, all other conditions remaining the same. Shown in Fig. 8 are patternation measurements performed for flow rates of 70–200 kg/h. The contour plots show the increasing definition of an 8 peak/rev nonuniformity in the high-flow region as the fuel flow increases. Also apparent is a slight rotation of the peaks in the clockwise direction with increasing flow. In this nozzle, both the fuel and the air rotate in the clockwise direction. The fuel has a lower effective tangential velocity compo-



Δp(psi)	0.5	1.5	3.8
P.I.	39.1	41.1	36.7
Min/Max	31.6	29.3	17.6
Alpha	80	71	63

Fig. 9 Effect of airside pressure drop.

nent than does the air; as the fuel momentum increases, an apparent counterclockwise shift in the fuel peaks results. The computed spray angle shows a slight increase. This is due to the greater penetration of the fuel into the outer swirler airflow. The outer airflow swirler contains eight vanes; this is responsible for the 8 lobe/rev pattern.

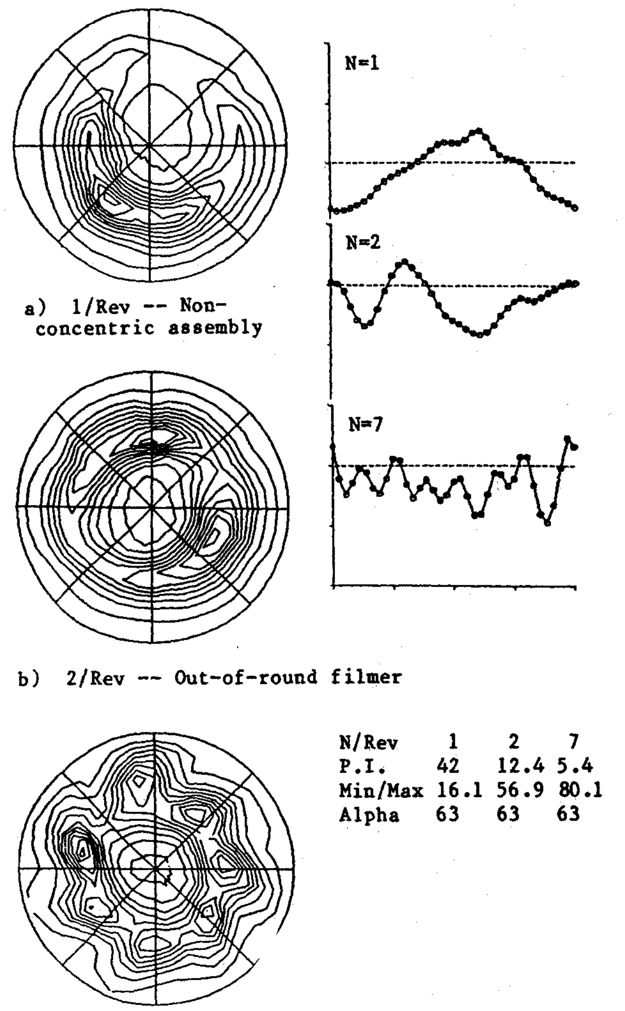
Airflow Rate

Shown in Fig. 9 are results obtained as the air flow rate, reflected by the airside pressure drop, is increased. The contour plots and calculated spray angle show that the increased airflow causes a decrease in spray cone angle. This is consistent with the observation that, in the downstream region, the radial component of the fuel momentum is directed outward and that the airflow momentum counteracts this outward motion.

Patternation System Applications

The primary application of this apparatus is the establishment of the influence of injector design parameters on spray distribution. Although the results of such tests will be discussed in detail in future publications, certain results are presented here for purposes of illustrating the system application. The most common type of maldistribution observed in the air-blast injectors tested to date is of the type illustrated in Fig. 10a. This 1 lobe/rev asymmetry can be caused either by the inner barrel of the injector being nonconcentric with the outer filming surfaces or by the inner barrel centerline being skewed relative to the centerline of the outer air swirler assembly. These misalignments can occur during the final assembly of the fuel injector. In-house studies are currently under way to evaluate the sensitivity of the spray maldistribution to these manufacturing tolerance factors.

Examples of higher order modes being present in the spray pattern are also given in Fig. 10. Figure 10b shows a 2 lobe/rev mode caused by an out-of-round inner filming surface. Figure 10c shows a 7 lobe/rev mode caused by wakes from an outer air swirler having a vane design with an inadequate gap/chord ratio.



N/Rev	1	2	7
P.I.	42	12.4	5.4
Min/Max	16.1	56.9	80.1
Alpha	63	63	63

Fig. 10 Effects of injector design parameters.

Conclusions

The results obtained to date with the above-described patternation system indicate that high-resolution measurements of the mass flux distribution produced by gas turbine injectors can be acquired by use of an extractive probing system. The system has proved to be reliable and economical to operate. In most cases, the spatial resolution achieved has been sufficient to trace the origin of the observed nonidealities to the aerodynamic and hydraulic design features responsible for their existence.

The work being performed with this apparatus focuses attention on two questions that have yet to be thoroughly addressed with respect to spray patternation. The first is whether the spray patterns observed under the conditions of these ambient pressure spray tests accurately reflect the patterns produced under high-pressure engine conditions. This bears directly on the procedure for scaling from engine conditions to ambient pressure and temperature conditions. Work has been performed in the past on the effects of elevated pressure on spray angle (radial distribution) and on spray mean droplet size, but no information on the effects of pressure on circumferential nonuniformity has been published. There is a need to conduct a limited number of high-resolution, high-pressure tests to confirm the generally held belief that low-pressure testing is a useful technique for evaluating injector performance.

The second question concerns the degree to which the injector-produced nonuniformities affect combustor performance. No systematic investigation of this nature has been published. A limited body of data has been acquired in engines instrumented with temperature sensors on turbine entrance vanes, which indicates that poorly performing injectors lead to worsened combustor exit temperature pattern factors. Soot production can be expected to increase due to regions of abnormally high fuel concentrations, but published results documenting the effect of spray pattern circumferential nonuniformity on burner soot emissions are not available. The conduct of definitive experiments to document the injector effects on combustor performance is complicated by the fact that such results will be dependent on the burner configuration. Burners characterized by long length, large amounts of dilution air, and high liner pressure loss can be expected to be relatively "forgiving" with respect to injector nonidealities. However, advanced high-pressure-ratio engines require that the burner be short in order to reduce the cooling air requirements, operate at high exit temperatures and thus have less dilution air available for profile tailoring, and operate with lower liner loss (less potential for rapidly mixing fuel and air) in order to maximize cycle efficiency. As a result, modern burners can be expected to be more sensitive to spray nonuniformity than has been the case in the past. Systematic evaluations of the degree to which combustors of varying characteristics react to injector nonidealities are required to provide a rational basis for establishing injector specifications—requirements for highly uniform sprays lead to high fuel injector unit costs, while loosened requirements can lead to higher engine maintenance costs.

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