JOURNAL OF PROPULSION AND POWER
Vol. 11, No. 2, March–April 1995

Dual-Spray Airblast Fuel Nozzle for Advanced Small Gas Turbine Combustors

Clifford E. Smith,* Eric J. Fuller,† and D. Scott Crocker‡
CFD Research Corporation, Huntsville, Alabama 35805
and
L. T. Mekkes§ and J. C. Sheldon¶
Delavan Inc., Des Moines, Iowa 50265

A novel dual-spray airblast fuel nozzle that has the potential of improved light-off capability and higher combustor turndown fuel-air ratio is being developed for advanced military small gas-turbine engines. Features of the nozzle include: 1) full integration of the combustor dome swirler and two airblast atomizers (pilot and main) into a single functional unit, 2) minimum fuel flow passages greater than 0.018 in., and 3) integration and optimization of the primary zone airflow and spray patterns to substantially increase combustor turndown fuel-air ratios. Nine research versions of the nozzle were designed, fabricated, and tested. Measurements of effective flow area (ACd), spray angle, atomization quality, and air velocity were used to screen the designs. The best nozzle configurations were tested for ignition and lean blowout in a single-nozzle combustor front-end at ambient conditions. To ascertain the effect of nozzle-nozzle interaction, the best configuration was tested in a three-nozzle combustor front-end. Identical ignition and lean-blowout results were obtained as compared to single-nozzle tests. The best nozzle design could be lit at a pressure drop of 1.25 in. of water and a fuel flow of 1.5 pph per nozzle.

I. Introduction

SMALL turboshaft military gas-turbine engines (~10 lb/s) are very dependent on the performance of fuel nozzles for combustor ignition, pattern factor, durability, combustion efficiency, smoke, emissions, etc. Fuel nozzles must adequately atomize and disperse liquid fuel into the combustor at various operating conditions, ranging from extremely low fuel flows (~5 pph) at startup to high fuel flows (~100 pph) at sea level takeoff. Future high-pressure ratio engines with increased cycle temperatures will require advanced fuel nozzles capable of very large turndown fuel flow (40:1) and fuel-air ratios (10:1).

Two types of fuel nozzles have been used in the past[1]: 1) the pressure-swirl atomizer (e.g., simplex, duplex, dual-orifice, etc.) and 2) the airblast atomizer. The pressure atomizer has a high susceptibility of small passages being fouled (plugged) during hot shutdown, and a strong tendency of high soot formation at high combustion pressures. In recent years, the airblast atomizer has been shown to be superior in atomization/mixing characteristics, plus it has greater turndown fuel flow ratio, thus making it the preferred nozzle compared to the pressure atomizer. However, the airblast atomizer does suffer from three severe limitations:

1) At startup conditions, the combustor air pressure drop is so low (~1.5 in. of water) that atomization, and thus ignition, is severely hindered.

2) At altitude conditions (low fuel flows), atomization can be poor due to fuel maldistribution in the prefilmer (caused by gravity effects).

3) Overall turndown fuel-air ratio is relatively low, between 4.0–6.0, depending on the primary zone airflow.

To circumvent these problems, a small pilot pressure-atomizing nozzle is added. A well-atomized spray is thus provided at startup and low-load operation, allowing for easy light-off and wide stability limits. At high fuel flows, all of the virtues of airblast atomization are maintained. A typical simplex-piloted nozzle has minimum fuel passages of 0.008 in.

The simplex-piloted airblast atomizer has been a successful fuel nozzle for the past decade, but recent developments have necessitated the need for an improved nozzle. First, the Army-wide conversion from JP4 to JP8 fuel will result in deterioration of atomization at engine startup due to higher fuel viscosity. The fuel pressure for the pilot nozzle at startup will have to increase, and in many instances such an increase is not possible. Second, higher fuel temperatures of advanced engines will result in a greater probability of plugging the pilot atomizer, especially during hot shutdown. And third, combustors are being designed for higher temperature rise, and associated higher turndown fuel-air ratios. Improvements are needed in primary zone fuel-air distribution if low smoke emission is to be maintained at full-power and good lean stability is to be maintained during rapid engine deceleration. Otherwise, air staging (e.g., variable geometry) or fuel staging (e.g., double annular combustor) is required, which adds unreliability, complexity, and/or weight to the engine.

A. Dual-Spray Airblast Atomizer Overall Design Considerations

An alternative to the simplex-piloted airblast nozzle is the dual-spray airblast nozzle. The pilot nozzle in the dual-spray airblast nozzle is a small diameter airblast nozzle. A schematic diagram of the concept is presented in Fig. 1. The dual-spray airblast atomizer consists of two fuel passages (designated pilot and main), and three air-passages (designated inner, mid and outer). Pilot fuel is discharged between the inner and midairstreams, whereas main fuel is discharged between the mid and outer airstreams. The high-velocity airstreams shear and atomize the liquid sheets into fine sprays. The airstreams are swirled by curved axial vanes, and all streams are coro-

Presented as Paper 93-2336 at the AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference and Exhibit, June 28–30, 1993; received Aug. 27, 1993; revision received April 29, 1994; accepted for publication June 3, 1994.

*Vice President/Engineering. Member AIAA.
†Project Engineer. Member AIAA.
‡Senior Engineer. Member AIAA.
§Senior Project Engineer.
¶Manager, Engineering Laboratory.

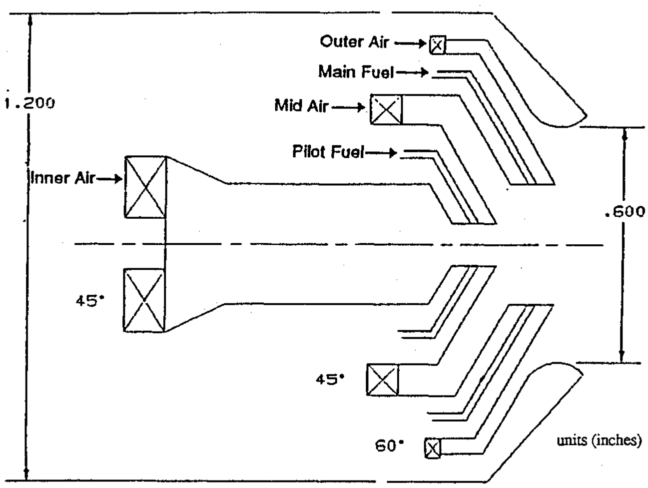


Fig. 1 Schematic of dual-spray airblast fuel nozzle (configuration 1e).

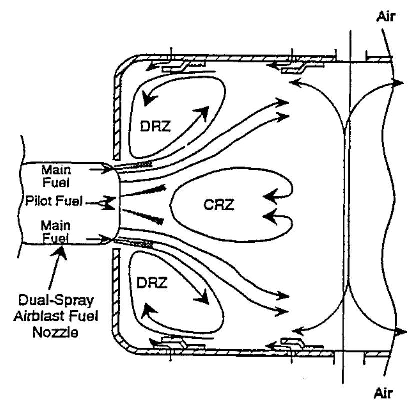


Fig. 2 Fuel and airflow patterns desired for combustor front-end.

tating. The dual-spray airblast nozzle is designed to pass all of the dome airflow except cooling flow (i.e., no dome swirler is used).

The purpose of having a small-diameter airblast atomizer for a pilot is to provide improved atomization at low fuel flows and low air pressure drops compared to a conventional airblast atomizer. For larger-diameter lips, gravity effects are more significant and the discharge flow area of the fuel is greater. Both of these effects combine to cause fuel puddling on the bottom of the discharge opening. For the dual-spray design, the pilot lip diameter was made small (i.e., 0.100 in.), thus reducing gravity effects. Every effort was made to ensure a uniform thin film at low fuel flows.

The main airblast atomizer is designed with a lip diameter of 0.310 in. The main fuel is discharged near the mass center of the nozzle airflow, thus promoting more uniform fuel-air distribution at high-load conditions.

B. Primary Zone Design Considerations

The dual-spray airblast atomizer is designed to control fuel-air ratio in the combustor primary zone such that larger turndown fuel-air ratios are possible. Advanced combustors will be required to operate at overall fuel-air ratios as high as 0.050, yet still maintain stable combustion at an idle fuel-air ratio of 0.010. Thus, the minimum design fuel-air ratio (that occurs during rapid engine deceleration when fuel flow change responds faster than airflow change) is 0.005. This gives a turndown fuel-air ratio of 10—almost double that of current engines.

An innovative combustor design approach is being studied to increase turndown fuel-air ratio. Instead of treating the primary zone as one lumped zone, the two recirculation zones in the combustor primary zone are treated as two independent and separately fueled reaction zones. By controlling the fuel-air distribution in each reaction zone, optimum turndown fuel-air ratio is possible. Figure 2 depicts the two recirculation zones desired in the primary zone: 1) the central recirculation zone (CRZ) created along each nozzle's centerline and 2) the dome recirculation zone (DRZ) caused by the sudden expansion of nozzle airflow discharging into the combustor. The CRZ is fueled by the pilot atomizer, and is used for combustor stability. The equivalence ratio of the CRZ is maintained near 1.0 at all operating conditions. The DRZ is fueled by the main atomizer and is designed to operate at an equivalence ratio ϕ between 1.0–1.2 at full-power conditions. The formation of soot typically occurs if local equivalence ratios exceed 1.8, and this will certainly occur somewhere in the primary zone (as it does in most aircraft gas-turbine combustors). However, soot oxidation should occur downstream of the primary zone in regions of high temperature and equivalence ratios less than 1.0.

This article will focus on the design and performance (ignition and lean-blowout) of the dual-spray airblast fuel nozzle at ambient conditions. First, design aspects will be discussed including the use of CFD analysis to define the effective flow areas of the candidate designs. Second, cold-flow test results (e.g., effective flow areas, spray angles, etc.) will be presented. Third, single-nozzle hot tests of the best concepts will be reviewed. And last, a three-nozzle test of the best nozzle configuration will be presented.

II. Dual-Spray Airblast Nozzle Designs

The design strategy of the dual-spray airblast atomizer is to control the airflow splits and spray angles to obtain CRZ fueled by the pilot nozzle and DRZ fueled by the main nozzle. To successfully accomplish this strategy, the following flow characteristics are desired: 1) two different spray angles are desired, the pilot spray angle being narrow (~90 deg) and the main spray angle being wide (~140 deg); 2) an effective flow area (ACd) of approximately 0.075 in.^{2}. The desired airflow splits between airflow passages are a) inner passage—10%, b) midpassage—55%, and c) outer passage—35%; 3) a strong CRZ on the nozzle centerline is desired to anchor the pilot flame; 4) a pilot spray with sufficient atomization to produce light-off at startup conditions; and 5) a pilot fuel flow number of 2.0, and a main fuel flow number of 8.0.

Four research nozzles were initially designed. The critical dimensions and swirl vane angles are shown in Fig. 3. Configuration 1 was the baseline configuration. The airflow swirl vanes were 45 deg inner, 45 deg mid, and 60 deg outer. Configuration 2 duplicated configuration 1 in every detail, except the midswirl vanes were changed from 45 deg to 60 deg, resulting in higher swirl, but a reduced overall ACd. Configuration 3 was the same as configuration 2, except the midair-passage gap was increased from 0.079–0.138 in. to produce the same overall ACd as configuration 1. Configuration 4 was the same as configuration 1 except for a reduction of the outer passage airflow to 25% of the total nozzle airflow, and an increase of the midpassage airflow to 65%. Also, the main fuel lip diameter was increased from 0.310 to 0.400 in. for configuration 4.

Configurations 1–4 were designed using the multiblock CFD code CFD-ACE.[2,3] The multiblock feature allowed the rather complex internal airflow passages to be meshed relatively easily. The calculation domain started just downstream of the swirl vanes in each passage, and extended into a dump combustor. The total pressure and flow direction were specified at each airflow inlet, and a loss coefficient was assumed[1] to account for the swirl vane pressure loss. (The swirl vane total pressure loss was very low, less than 10% of the nozzle air pressure drop, thus reducing the sensitivity of the predictions to the assumed loss coefficient across the vanes.) The ACd was determined by calculating the mass flow through the nozzle and using the equation:

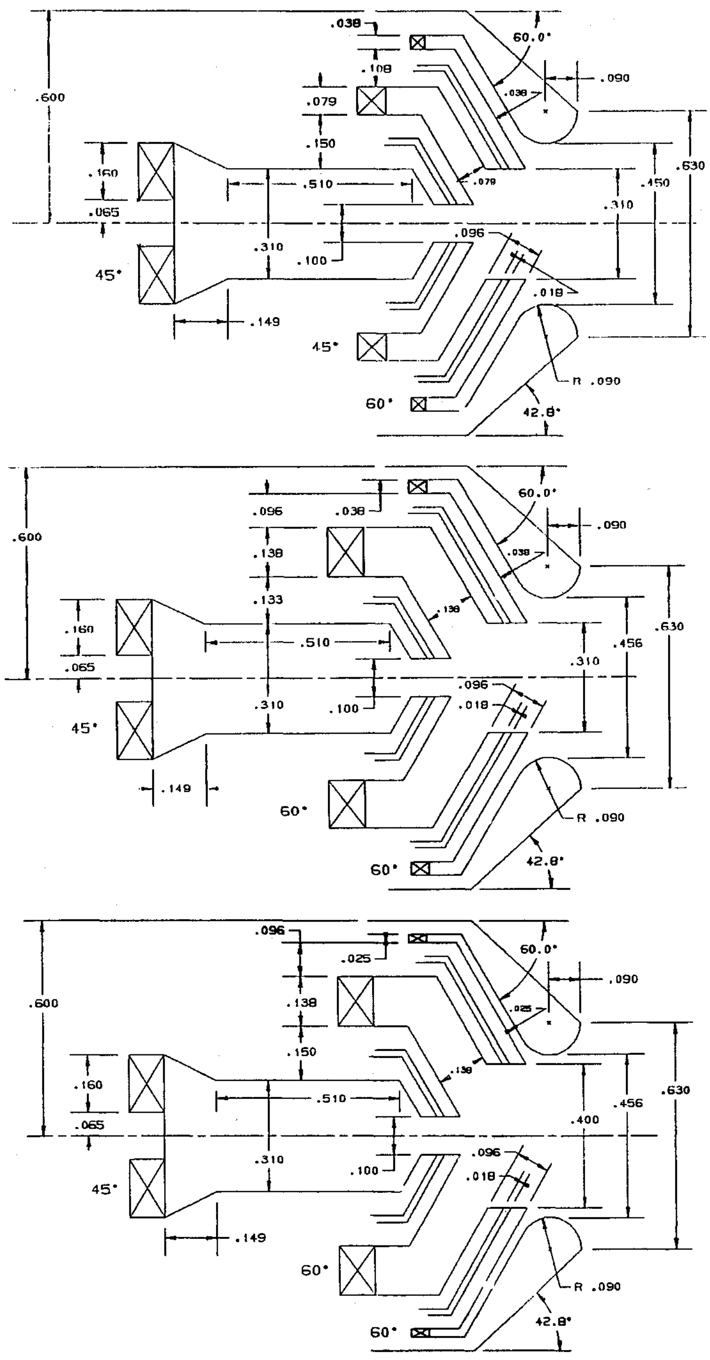
$$\text{ACd} = (\dot{m}/\sqrt{2\rho\Delta P}) \qquad (1)$$

where

$\dot{m}$ = mass flow
ρ = air density
ΔP = total pressure upstream of vanes minus ambient pressure

A sample CFD calculation of configuration 1b (to be identified later in this article) is shown in Fig. 4. Over 30 CFD calculations were performed to determine nozzle dimensions needed to obtain design flow areas (ACd). Predicted ACd of each individual passage and each nozzle is shown in Table 1. Note that the sum of the individual passage ACds does not equal the overall nozzle ACd, indicating that there was flow interaction between airflow passages. The midair-passage had a 20% increase in airflow when all passages were flowing compared to flowing separately.

Initial testing showed configuration 1 to have the most potential. However, there were two concerns that had to be addressed. First, it appeared that the outer passage airflow was not staying attached to the outer shroud, causing lower than desired spray angles. Second, main fuel impinged on the outer shroud of the nozzle, resulting in poor atomization. Five outer shroud modifications, as shown in Fig. 5, were designed to address these concerns. Configurations 1a and 1b were the same as configuration 1, except the outer shroud was flared to 60 and 45 deg, respectively, instead of 90 deg as was the case for configuration 1. Configurations 1c–1e were the same as configuration 1a, except the outer shroud diameter was



Configuration 1
(Configuration 2
the same except 60°
mid passage vanes)

Configuration 3

Configuration 4

Fig. 3 Design features of dual-spray airblast fuel nozzle: configurations 1–4.

Table 1 Nozzle ACd, in.[2]

Configuration	Inner-air (separately)		Midair (separately)		Outer-air (separately)		Total (all together)	
	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured
1	0.006	0.007	0.032	0.035	0.023	0.024	0.075	0.076
2	0.006	0.007	0.023	0.024	0.023	0.024	0.057	0.058
3	0.006	0.007	0.033	0.038	0.023	0.023	0.076	0.081
4	0.006	0.007	0.047	0.052	0.018	0.017	0.076	0.080
1a	0.006	0.007	0.032	0.035	0.023	0.024	0.075	0.076
1b	0.006	0.007	0.032	0.035	0.023	0.024	0.075	0.076
1c	—	—	—	—	—	—	—	0.084
1d	—	—	—	—	—	—	—	0.085
1e	—	—	—	—	—	—	—	0.086

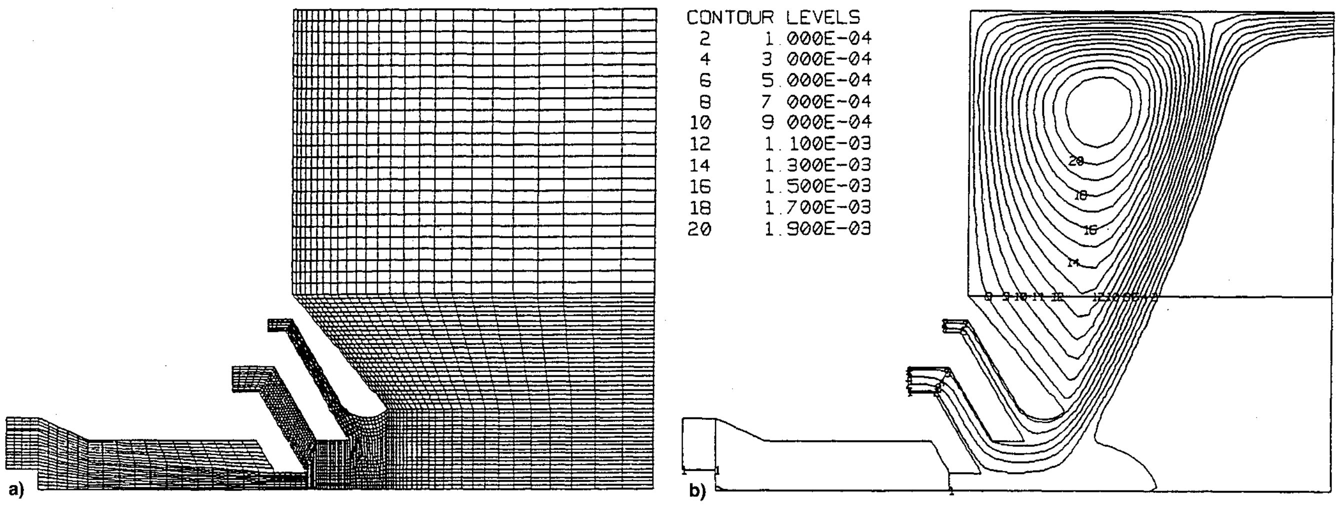


Fig. 4 Sample CFD calculation for configuration 1b: a) multibock grid and b) streamline contours (kg/s).

increased to 0.50, 0.55, and 0.60 in., respectively, from the 0.45 in. of configuration 1a. In addition, the outer shroud flare angles for configurations 1e, 1d, and 1e were reduced to 56.1, 52.2, and 48.4 deg, respectively, from 60 deg for configuration 1a.

For this study at ambient conditions, the research nozzles were fabricated from brass to reduce development costs. Each component of the nozzle was designed and fabricated in a modular manner, and then assembled together to form the fuel nozzle. Thus, the inner airflow swirler was inserted into the inner wall of the primary fuel passage, which was inserted into the outer wall of the primary fuel passage, etc. Figure 6 shows an example of the nozzle parts. Atomizer parts were epoxied together to permit easy modification and/or changes to the basic design.

III. Combustor Rig

A three-nozzle sector combustor rig was used for ignition/blowout testing. The rig could be used in the single-nozzle mode (i.e., one fuel nozzle was positioned in the center opening and the other two nozzle openings were plugged), or the three-nozzle mode. The combustor was rectangular in shape for optical viewing and manufacturing convenience, and did not have sidewalls, thus avoiding unwanted secondary flow patterns. A schematic cross-sectional view of the rig is shown in Fig. 7. The combustor consisted of 1) fuel nozzle(s), 2) combustor dome, and 3) combustor liners with primary holes and liner cooling holes.

Three plenums fed airflow into the combustor; one plenum was attached to the combustor dome and distributed airflow into the fuel nozzle(s), and the other two plenums were attached to the liners and distributed airflow into the primary and cooling holes. The combustor dome was 2.5 in. in height. The fuel nozzles were mounted in the dome through 1.20-in.-diam orifices, spaced 3.14 in. apart. There were two 0.234-in.-diam primary holes/liner/nozzle in a laterally staggered arrangement. The primary holes were located 1.75 in. downstream of the combustor dome. Two sets of cooling holes were positioned in each liner. One set of cooling holes was located 0.55 in. upstream of the primary holes and louvers deflected the cooling airflow upstream toward the dome. The second set of cooling holes was located 0.55 in. downstream of the primary holes and louvers deflected the cooling airflow downstream toward the combustor exit. A schematic diagram of the combustor showing the design airflow splits is presented in Fig. 8.

Pressure taps were located in each of the three plenums to measure and set air pressure drop during testing. Two fuel lines were connected to each fuel injector, one flowing fuel to the pilot nozzle and one flowing fuel to the main nozzle. Pilot and main fuel flows were separately controlled. Jet A fuel was used throughout hot testing. Inlet fuel temperature was approximately 70°F.

IV. Cold Flow Tests

Nonreacting nozzle flow tests were performed at Delavan test facilities. Measurements of ACd, spray angle, axial velocity, and SMD were made to screen the nozzle designs. ACd measurements were made using calibrated flow orifices and delta pressure gauges; accuracy was ±2.0%. Spray angles were determined from long exposure photographs; estimated accuracy is ±10 deg. Axial velocities and SMD were measured using a single-component phase Doppler particle analyzer (PDPA); estimated accuracy is ±3.0%. The results of the tests are discussed below.

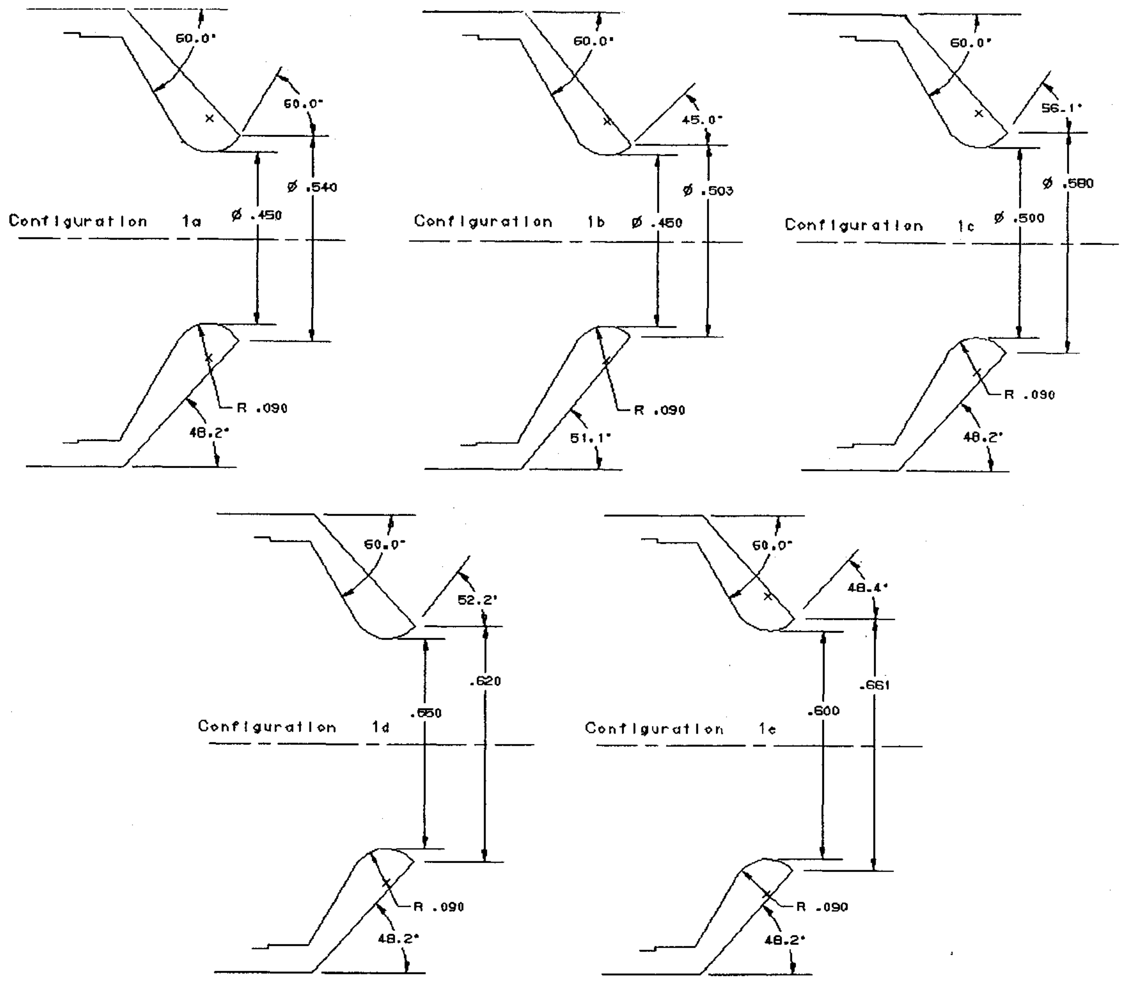


Fig. 5 Outer shroud modifications.

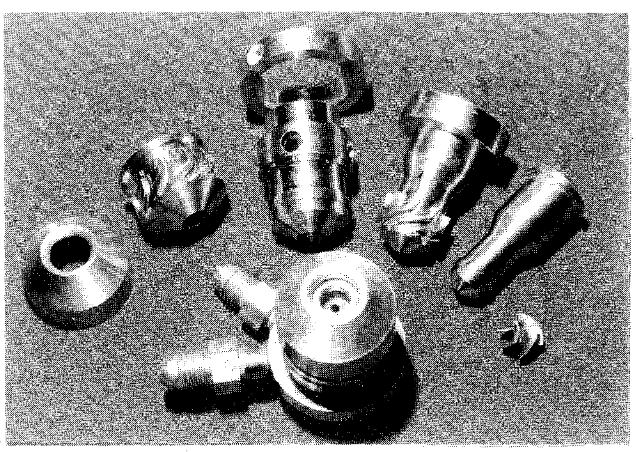


Fig. 6 Fuel nozzle components.

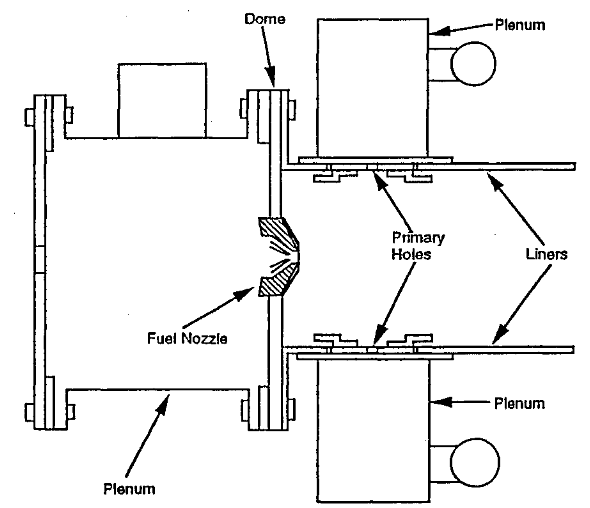


Fig. 7 Schematic of combustor.

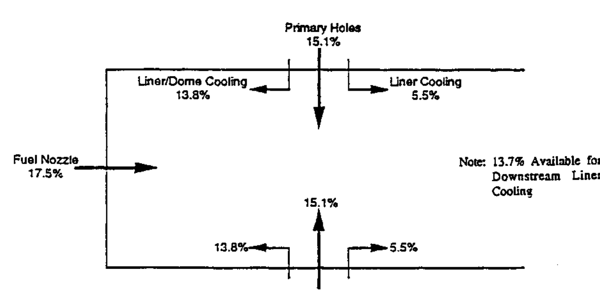


Fig. 8 Combustor airflow splits.

A. Effective Flow Area (ACd) Measurements

ACd measurements were made for configurations 1–4. Measurements were taken both for individual passages as well as the entire nozzle configuration, as shown in Table 1. Good overall agreement can be seen between predictions and measurements. The overall ACd was within 7% for each design. The largest discrepancy occurred for the midair-passage, where predictions were constantly low by about 5–10%. Later inspection of the CFD predictions revealed the assumed loss coefficient for the swirl vanes of the midair-passage was too high. However, in an engineering sense, the overall predictions of flow area and flow splits for each nozzle design compared well with measurements.

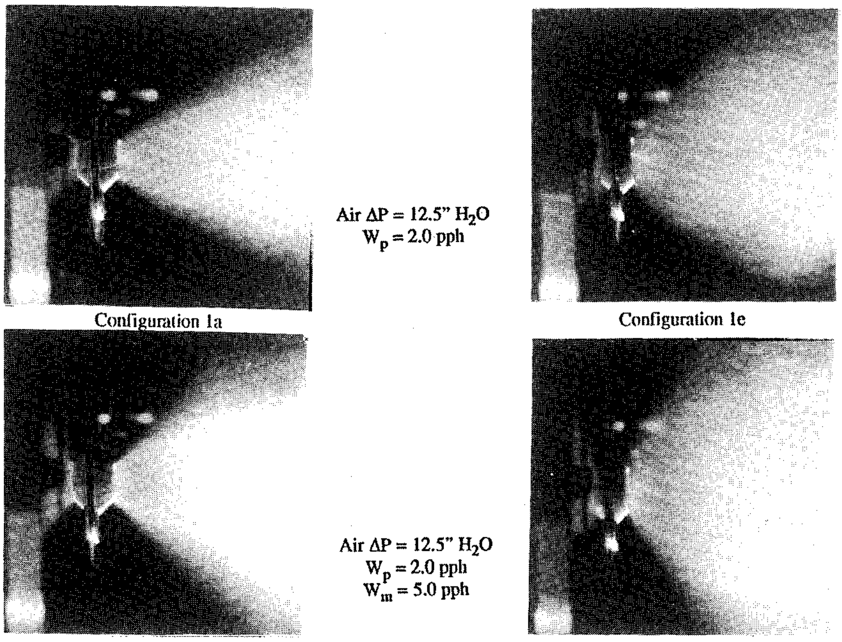


Fig. 9 Comparison of spray angles between configurations 1a and 1e.

ACd measurements were also taken for configurations 1a–1e, and they are also shown in Table 1. Configurations 1, 1a, and 1b had identical ACds. For configurations 1c–1e, increasing the outer shroud diameter slightly increased the airflow through the outer passage. The ACd for configuration 1e was 0.086 in.^{2}.

B. Spray Measurements

The spray from each of the nine dual-spray airblast atomizers was photographed discharging into the ambient environment. Spray tests were run at four flow conditions: 1) air pressure drop of 2-in. H_2O and pilot fuel flow of 2 pph, 2) air pressure drop of 12.5-in. H_2O and pilot fuel flow of 2 pph, 3) air pressure drop of 12.5-in. H_2O and main fuel flow of 5 pph, and 4) air pressure drop of 12.5-in. H_2O, pilot fuel flow of 2 pph and main fuel flow of 5 pph.

Flow condition 1 corresponded to a typical engine startup condition. Flow condition 2 had the same air pressure drop percentage $\Delta P/P$, and fuel-air ratio as a typical idle condition, and will be called the simulated idle condition in this article. Flow condition 4 will be called the simulated full-power condition. During the spray tests, it was observed that main fuel impinged on the outer shroud for configurations 1–4, 1a and 1b, resulting in less than desired atomization and potential carbon problems. In contrast, configuration 1e did not wet the outer shroud, and at the same time produced a much wider spray angle.

Figure 9 presents long-exposure photographs of the spray from configurations 1a and 1e at flow conditions 2 and 4. The difference in pilot and main spray angles is evident, as well as the increase in spray angles for configuration 1e compared to configuration 1a. For configuration 1e, the pilot spray angle was about 90 deg, and the main spray angle was about 135 deg.

C. PDPA Measurements

A single-component aerometrics PDPA was used to measure the axial air velocity at the nozzle exit, and to determine a line-averaged SMD of the spray 1.0 in. downstream of the nozzle exit. Only configurations 1–4, 1a, and 1b were tested using the PDPA. All of these configurations except configuration 3 exhibited small CRZs on the nozzle centerline. For configuration 1a, a CRZ of about 0.25 in. in diam was measured on the nozzle centerline.

The line-averaged SMDs of the tested configurations were all approximately the same: 1) 36 μm for flow condition 1, and 2) 25 μm for flow condition 2. Line-averaged SMD is the sum of local SMDs (along a line through the spray centerline) divided by the number of measurement locations. Line-averaged SMD should not be confused with the SMD for the entire nozzle spray.

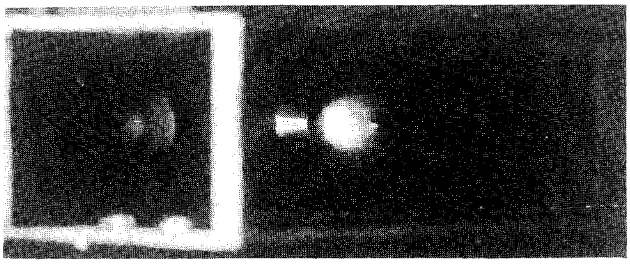
V. Combustion Tests

A. Single-Nozzle Tests

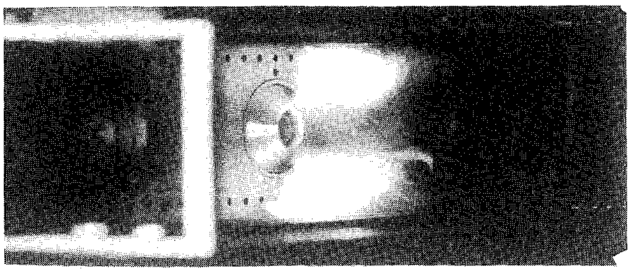
All hot tests were performed at Delavan. Ignition and lean-blowout tests were performed at two airflow pressure drops: 1) 2-in. H_2O and 2) 12.5-in. H_2O. For ignition tests, the airflow pressure drop was set the same for all three plenums. At a specified pilot fuel flow, a handheld spark ignitor (approximately 4 J tip energy sparking at one spark per second) was positioned near the exit of the fuel nozzle. Once ignition occurred, the fuel flow was slowly reduced until blowout occurred. Once the lean-blowout fuel flow was established, ignition tests were performed at the same, or nearly the same, fuel flow. In most instances, the ignition and blowout fuel flows were almost identical. Repeat runs were often performed, and the results were very consistent.

In initial tests with configurations 1–4, configuration 1 was shown to be the best in terms of startup ignition. Figure 10a shows configuration 1a (which performed similar to configuration 1), operating on the verge of lean-blowout at an air pressure drop of 2.0-in. H_2O, and a pilot fuel flow of 3.0 pph. The flame was anchored in the CRZ, and appeared as a small bulb about the diameter of the nozzle exit diameter. However, at a higher pressure drop (12.5 in. of H_2O), which is more representative of idle conditions, the flame became anchored in the DRZ near blowout, not the CRZ. Figure 10b shows the flame at the higher air pressure drop. Thus, configuration 1a, although meeting some of the design criteria, was not totally successful.

Configuration 1e proved to be a much better design. Figure 11a shows the flame of configuration 1e at near startup conditions (air pressure drop of 1.5-in. H_2O, pilot fuel flow of 2.0 pph), whereas Fig. 11b shows the flame at near simulated idle conditions (air pressure drop of 12.5-in. H_2O, pilot fuel flow of 4.0 pph). At startup, the flame was held in the CRZ-like configuration 1a, but the flame was much larger and was anchored much closer to the nozzle exit. Configuration 1e

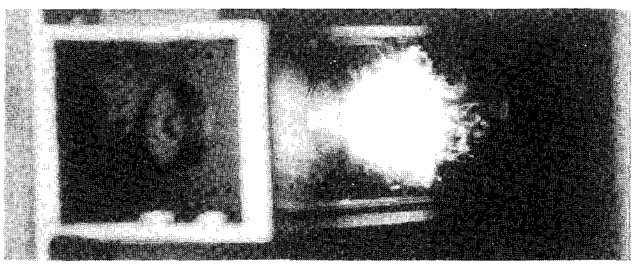


a)

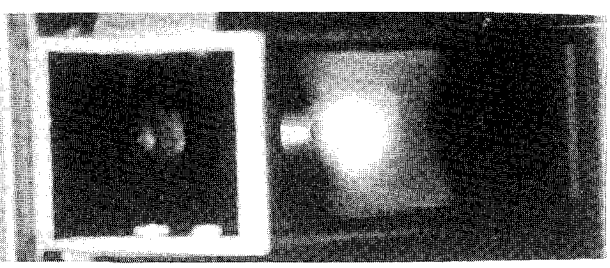


b)

Fig. 10 Single-nozzle flow results near blowout: configuration 1a: a) air ΔP = 2.0-in. H_2O, W_p = 3.0 pph and b) air ΔP = 12.5-in. H_2O, W_p = 4.5 pph.



a)



b)

Fig. 11 Single-nozzle flow results near blowout: configuration 1e: a) air ΔP = 1.5-in. H_2O, W_p = 2.0 pph and b) air ΔP = 12.5-in. H_2O, W_p = 4.0 pph.

was able to light-off at an air pressure drop as low as 1.25-in. H_2O and a pilot fuel flow of 1.5 pph, substantially less than configuration 1a. The ignition process for configuration 1e was also much easier than for configuration 1a (i.e., ignition was much less sensitive to the position of the ignitor). At simulated idle conditions, the flame was anchored in the CRZ, and a blue flame was observed in the DRZ. Hence, most of the pilot fuel was consumed in the CRZ as designed.

When the main fuel was added, the appearance of a luminous flame in the DRZ was observed as designed. Figure 12 shows two views of the flame for configuration 1e at a simulated full-power condition (air pressure drop of 12.5-in. H_2O, pilot fuel flow of 2 pph, and main fuel flow of 5 pph). At this air pressure drop, lean-blowouts by reducing main fuel flow were recorded both with pilot fuel flow (at 2 pph) and without pilot fuel flow. Much lower blowout main fuel flows were obtained (3 vs 5 pph) with the pilot operating. In addition, at blowout of the DRZ, the CRZ (being fed by the pilot fuel flow) remained lit.

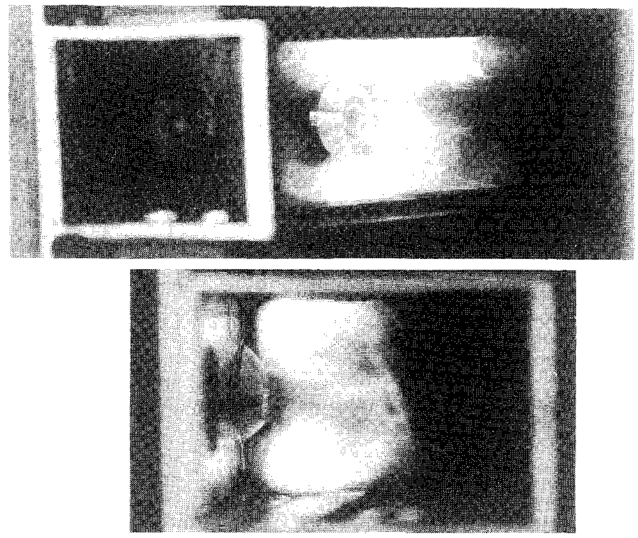
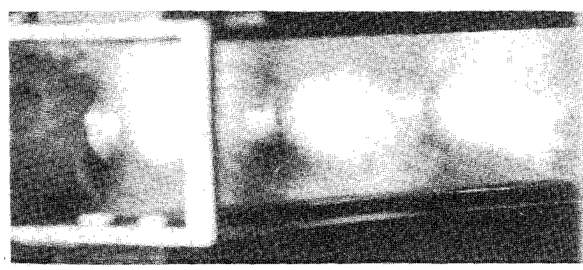


Fig. 12 Flow structure at simulated full power: configuration 1e: air ΔP = 12.5-in. H_2O, W_p = 2.0 pph, and W_m = 5.0 pph.

a)



b)

Fig. 13 Three-nozzle testing: configuration 1e: a) air ΔP = 1.25-in. H_2O, W_p = 2.5 pph and b) air ΔP = 12.5-in. H_2O, W_p = 5.0 pph.

B. Three-Nozzle Tests

Two additional nozzles of configuration 1e were fabricated so that a set of three nozzles could be tested in the combustor rig. This test was performed to insure the single nozzle tests were valid for an annular combustor. Photographs of the flames during three-nozzle testing are shown in Fig. 13. Figure 13a shows the combustor at near startup conditions (air pressure drop of 1.25-in. H_2O, and pilot fuel flow per nozzle of 2.5 pph). By comparing Fig. 13a with Fig. 11a, it can be seen that the flame appearance is very similar. Ignition and lean-blowout fuel flows were essentially identical for both single-nozzle and three-nozzle tests. To further confirm the validity of the single-nozzle tests, Fig. 13b presents the three-nozzle flame photographs at nearly the same conditions as Fig. 11b.

The three-nozzle tests were also used to check for flame propagation between nozzles. After igniting the center nozzle at near startup conditions (air pressure drop of 1.5-in. H_2O, and pilot fuel flow of 2 pph per nozzle) with a hand-held spark ignitor, the pilot fuel flow was increased until the flame propagated to the outer nozzles. The propagation occurred at a pilot fuel flow of 2.5 pph per nozzle.

VI. Conclusions

A dual-spray airblast fuel nozzle is being developed for advanced small gas-turbine combustors. The nozzle promises to have less susceptibility to plugging/fouling and to provide higher combustor turndown fuel-air ratio than conventional simplex-piloted airblast fuel nozzles. This study mainly focused on the engine start-up characteristics of the nozzle. Nine different nozzle configurations were tested in a single-nozzle combustor front-end for ignition and lean-blowout at ambient conditions (air pressure drop of 2-in. H_2O for simulated startup, and 12.5-in. H_2O for simulated idle). Findings of this study were as follows:

1) The outer shroud of the dual-spray airblast fuel nozzle had a strong influence on nozzle performance, both in terms of spray characteristics, flame characteristics, and ignition/lean-blowout limits.

2) The best performing nozzle (configuration 1e) had good ignition characteristics at engine startup conditions. Ignition was accomplished at an air pressure drop of 1.25 in. of H_2O and 1.5 pph per nozzle.

3) The best performing nozzle (configuration 1e) produced all flame characteristics deemed necessary for high combustor turndown fuel-air ratio.

4) Single-nozzle combustor ignition tests were shown to be identical to three-nozzle tests.

Acknowledgments

The authors express their appreciation to the Aviation Applied Technology Directorate, U.S. Army, Aviation and Troop Command, Fort Eustis, Virginia for funding this work under Contract DAAJ02-92-C-0031, and to Gary Butler, Army Technical Monitor.

References

[1]Lefebvre, A. H., *Gas Turbine Combustion*, Hemisphere, New York, 1983.

[2]Owens, S. F., "CFD-ACE: Command Language Reference Manual," CFD Research Corp. Rept. GR-92-6, Aug. 1992.

[3]Avva, R. K., "CFD-ACE: Theory Manual," CFD Research Corp. Rept. GR-93-1, March 1993.