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EMISSION AND PERFORMANCE OF A LEAN-PREMIXED GAS FUEL INJECTION SYSTEM FOR AERODERIVATIVE GAS TURBINE ENGINES

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ABSTRACT

A dry-low-NOx, high-airflow-capacity fuel injection system for a lean-premixed combustor has been developed for a moderate pressure ratio (20:1) aeroderivative gas turbine engine. Engine requirements for combustor pressure drop, emissions, and operability have been met. Combustion performance was evaluated at high power conditions in a high-pressure, single-nozzle test facility which operates at full baseload conditions. Single digit NOx levels and high combustion efficiency were achieved. A wide operability range with no signs of flashback, autoignition, or thermal problems was demonstrated. NOx sensitivities to pressure and residence time were found to be small at flame temperatures below 1850 K (2870 F). Above 1850 K some NOx sensitivity to pressure and residence time was observed and was associated with the increased role of the thermal NOx production mechanism at elevated flame temperatures.

INTRODUCTION

The achievement of low NOx emissions is essential to the viability of any gas turbine to be used in large-scale industrial applications such as electrical power generation. Governmental regulations and increasing environmental awareness can be expected to continue to drive acceptable emission levels downward. For these reasons, most turbine manufacturers have undertaken efforts (Solt and Tuzson, 1993) to develop combustion systems having the potential for achieving the lowest possible NOx levels while not significantly increasing the cost of the combustion system. Although the injection of water or steam and catalytic exhaust gas treatment are two NOx control strategies that have been put into use, the cost associated with these systems is significant. An industry goal is to develop approaches not requiring such treatment. Two approaches that have received high levels of development attention to attain this goal are the rich-quench, lean-burn (RQL) and lean-premixed NOx control strategies.

The RQL low-NOx control strategy, in which first fuel-rich then fuel-lean combustion is employed, has excellent operability and is the subject of ongoing development efforts (Rizk and Mongia, 1991). Although this approach does not have the possible flashback/autoignition problem of premixed systems for very high inlet temperature applications, the NOx control potential is limited by the ability of the quench process to rapidly and uniformly dilute the fuel-rich mixture. Improper execution of the quench process will result in the generation of local high temperatures and thus thermal NOx production. Efforts therefore continue to be focused on premixing systems.

Adoption of the lean-premixed approach for natural-gas-fired aeroderivative engines, which have relatively small combustor volumes available to perform both the fuel-air premixing task and the post-flame zone CO oxidation task, are expected to produce less than 25 ppm NOx (@ 15% O_2) (Leonard and Stegmaier, 1993). Large, low-pressure heavy machines are expected to approach "single-digit" NOx levels (Aigner and Muller, 1992 and Becker et al., 1986). These levels are significantly lower than those envisioned only a few years ago (Angello and Lowe, 1989).

Prior combustion studies were conducted by United Technologies to investigate lean-premixed and direct injection dry-low-NOx concepts applicable to moderate-pressure-ratio aeroderivative engines (McVey et al. 1992). Results indicated that although the lean direct injection approach had excellent operability characteristics, the NOx control potential was inferior to that for the lean-premixed system. Several lean premixed concepts were evaluated for the ability to control NOx while maintaining adequate stability. Two of the lean-premixing concepts, the aero-vane injector and the perforated plate injector, achieved excellent NOx control; however, a large number of injection sites was required. (The aero-vane injector incorporated hundreds of fuel injection orifices; the perforated plate injector consisted of premixing tubes each with several injection sites.) Subsequent to that reported work, a premixing concept, featuring design simplicity, and fewer injection sites produced even lower NOx levels and exhibited excellent stability margin. The swirl-stabilized combustion zone produced by this device featured a large recirculation region. As reported for the aero-vane device, the large recirculation zone produced in swirl stabilized combustion systems does not produce adverse effects on NOx, even when long residence times exist. Other studies (Nicol et al., 1993) have since theoretically confirmed that thermally-generated NOx, which is residence time dependent, is only a small contributor to NOx emissions in a properly designed premixing combustion system for moderate pressure ratio engines. This simplified-design concept, hereafter referred to as the tangential entry (TE) concept, is the subject of this paper.

One of the challenges to the development of a practical lean premixed system is to assure that sufficient flame stability margin and robust operation is achieved at high power (baseload operation) while maintaining excellent NOx control. Robust operation at baseload implies the absence of flashback/autoignition and thermal distress as the airflow and fuel flow are deviated from normal operating conditions. The premixing system must also demonstrate the ability to maintain high combustion efficiencies over the entire engine operating envelope.

This paper summarizes efforts undertaken to develop the TE concept for application in the United Technologies Turbo Power FT8 engine. A diagram showing how the concept is implemented in the engine is shown in Fig. 1. When contrasted with the conventional burner (shown above the centerline in the figure), the most notable design impact is the bulging of the diffuser case and the canting of the burner. This flow path change provides sufficient flow area for the diffuser discharge air to pass between the fuel feed lines and injector support struts and reach the fuel injector inlet air slots located on the outboard section of the nozzle. For engine design simplicity, the number of fuel injectors is minimized. The initial engine design called for 18 nozzles to be circumferentially distributed about an annular burner. Each nozzle was required

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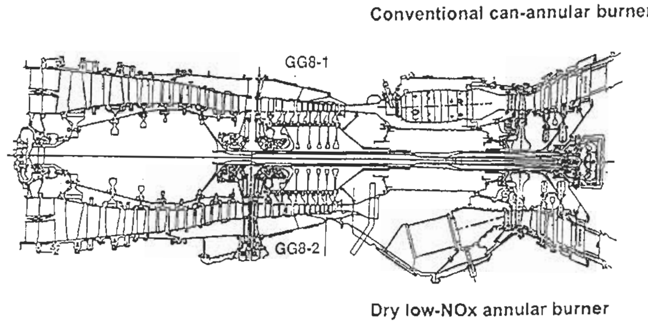


FIGURE 1. LARGE FLOW CAPACITY DRY LOW NOX TE NOZZLE COMBUSTION SYSTEM INCORPORATED IN FT8 ENGINE.

to pass a high level of airflow with an acceptable airside pressure drop level. The nozzle designed and evaluated to meet this flow requirement was designated the TE92 nozzle. As the engine design progressed, further pressures to reduce the number of nozzles and the individual nozzle pressure drop resulted in a decrease in the number from 18 to 16. This even more aggressive nozzle design was designated as TE93C in this paper.

APPROACH

The combustor development effort is planned as a three-phase effort: (1) single-nozzle tests to develop the fuel premixing system; (2) sector tests to develop the combustor cooling scheme and piloting system required for low power operation; (3) engine tests to develop control strategies and document engine emission performance. This paper describes that portion of the first phase which dealt with the experimental evaluation of the behavior of the TE nozzle under combusting flow conditions. The following three sections describe the TE nozzle, test apparatus, and the test conditions.

Tangential Entry Nozzle

The terminology "tangential entry" was adopted to reflect the air scroll orientation which imparts the maximum tangential momentum to the air as it enters the combustion chamber. The high-flow capacity TE nozzle consists of two main components: a scroll swirler and a conical centerbody, Fig. 2. Two cylindrical arc scrolls with radius (R), are offset a distance (S) from the plane of symmetry (Fig. 2b), and mounted between two baseplates (Fig. 2a). The dimensions shown are for the 18-nozzle engine design (TE92). The inner edges of the scrolls are diametrically-opposed to one another and tangent to a circle having a diameter (D). The burner airflow enters the swirler through the two rectangular inlet slots, with length (L), formed by the scroll offset, and exits through a circular hole (of a diameter equal to that of the tangent circle). Main gas fuel is supplied to two manifolds and injected into the inlet air from an array of orifices located on the outer scroll surface opposite the trailing edge of the opposing scroll. The orifice array specifications are detailed below. The conical centerbody, which could allow for the incorporation of liquid fuel hardware, has a base diameter equal to the swirler exit diameter and is tapered at an angle which places its apex at the end of the inlet slot.

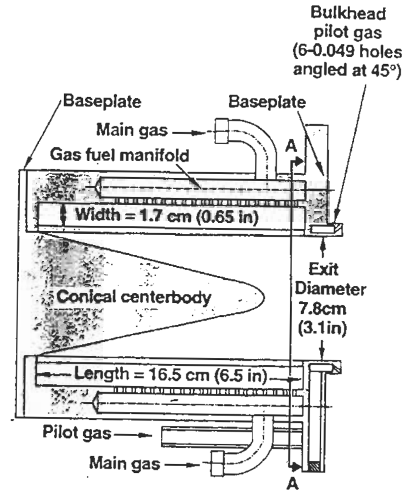
The geometry as described above formed the framework for the TE nozzle baseline design. During development, modifications were made to accommodate:

(1) Piloting - low-emission operation over the entire power range required some form of staging.

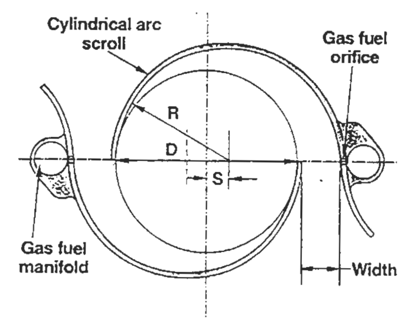
(2) Airflow capacity - a reduction in air pressure loss, lower than the pressure loss achieved by the original concept demonstration, was necessary to improve engine heat rate and overall cycle efficiencies.

(3) Fuel-air premixing - higher levels of the fuel and air premixing by the TE nozzle was desired to obtain single-digit NOx control at baseload conditions.

During the initial screening tests, it was determined that operation down to 40% power could be achieved through the use of a pilot located at the centerbody tip. For this injector development program, a "bulkhead pilot" was incorporated into the baseline design which extended stable, efficient operation down to idle conditions, Fig. 2a. This allowed the cone to be dedicated for liquid fuel in a separate development effort. The pilot consisted of an array of



2A.) SIDE VIEW.



2B.) CROSS SECTION A-A.

FIGURE 2. SCHEMATIC DIAGRAM OF TE92 FUEL NOZZLE GEOMETRY AND DIMENSIONS.

orifices located at the nozzle exit plane such that fuel was directed into the recirculation region formed as the nozzle flow expanded into the combustion chamber.

Airflow capacity evaluations were conducted using cold-flow plexiglass models of the TE nozzle. An exit diameter of 7.8 cm (3.1 in) and a slot length of 15.8 cm (6.2 in) were selected based upon the available space in the engine. Parametric variations of the inlet slot width were made to determine the influence of slot width on the nozzle effective area, Fig. 3. These results, in addition to analytical predictions, were used to specify the TE92 dimensions shown in Fig. 2.

A 4% airflow pressure drop was achieved for the TE92 nozzle. However, it was desired to further decrease the airflow pressure loss from 4% to 3% and decrease the number of nozzles per engine from 18 to 16. Furthermore, cone tip thermal distress problems during off-design operation (discussed later) led to the incorporation of an airflow passage on the axis of the cone. The airflow admitted to this passage was counter-swirled relative to the main flow by installing a 45-degree simple swirler in the passage. Air flowrates constituting 12% of the total primary zone airflow produced favorable performance (Fig. 4). The geometric characteristics of this more aggressive design (TE93C) are compared with the TE92 in Table 1:

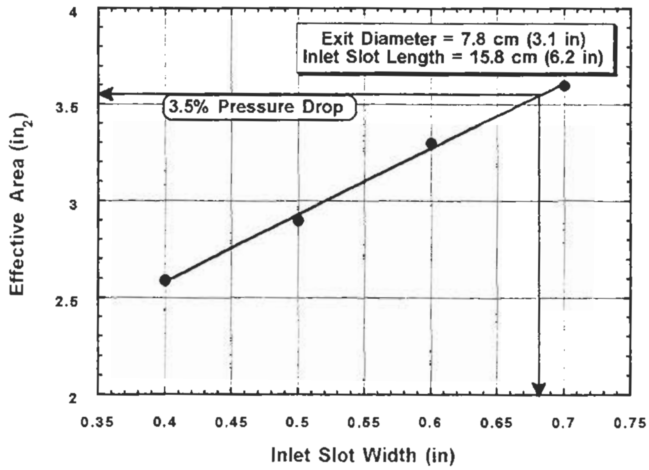


FIGURE 3. TE NOZZLE EFFECTIVE AREA DEPENDENCE ON INLET SLOT WIDTH.

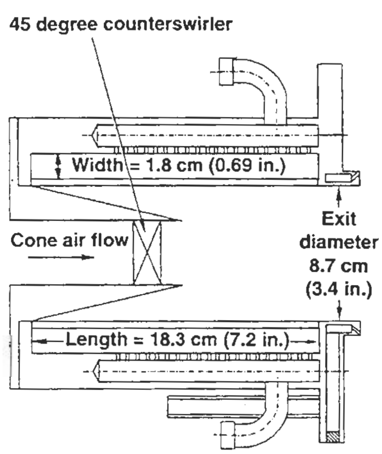


FIGURE 4. SCHEMATIC DIAGRAM OF TE93C FUEL NOZZLE GEOMETRY AND DIMENSIONS.

TABLE 1. TE NOZZLE DIMENSIONS AND AIRFLOW CAPACITY

	TE92	TE93C
Length (L)	16.5 cm (6.5 in)	18.3 cm (7.2 in)
Width (W)	1.7 cm (0.65 in)	1.8 cm (0.69 in)
Diameter (D)	7.8 cm (3.1 in)	8.7 cm (3.4 in)
Combustor Airflow	65%	67.5%
Airflow Capacity	2.6 kg/s (5.7 pps)	2.9 kg/s (6.3 pps)
Pressure Drop	4%	3%
Nozzles per Engine	18	16

Gas jet penetration calculations, using a correlation for a gas jet injected normal to a crossflow (Hautman et al., 1991), were used to specify the number and diameter of the fuel orifices. The fuel pressure drop calculated for baseload fuel flows, orifice spacing, and the inlet slot geometry were combined into a parameter (Holdeman, 1991) for optimizing the mixing of penetrating jets. This configuration was referred to as medium penetration.

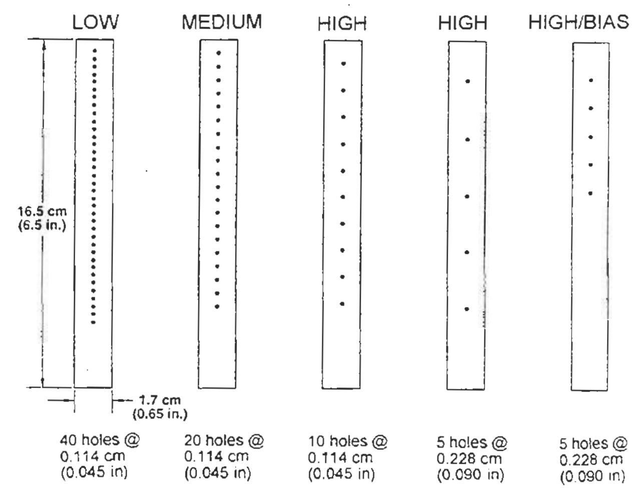


FIGURE 5. TE92 MAIN GAS FUEL ORIFICE CONFIGURATIONS.

Variations in the main gas fuel orifice array were made to improve the level of fuel-air premixing produced by the medium penetration configuration. Five different orifice arrays having three different penetration levels were evaluated for the ability to control NOx at baseload conditions, Fig. 5. The calculated penetrations were approximately 25%, 50%, and 90% percent of the slot width and were identified as low, medium, and high penetration, respectively. Two variations of the high penetration case were tested. The first (10 holes per inlet) achieved high penetration, but with a fuel pressure drop greater than practical for an engine fuel system. The second (5 holes per inlet) achieved high penetration with a fuel pressure drop that met the engine limitations. Configurations that produced low penetration were comprised of a large number of small orifices while high-penetration configurations were comprised of a smaller number of large-diameter orifices. The span over which fuel was injected into the inlet slot was maintained approximately the same for the low, medium, and high penetration cases. A fourth configuration maintained high penetration and biased the fuel toward the downstream end of the inlet slot.

Single Nozzle Rig (SNR) Test Facility

The SNR test facility (Fig. 6) and related systems permitted independent control of airflow, gas fuel flows, inlet temperature, inlet pressure and combustor pressure. The SNR consisted of a series of circular cross-section components flanged together. Facility air was metered by a venturi before being heated by a non-vitiating heater. The inlet static pressure (Pinlet) and inlet stagnation temperature (Tinlet) of the air were measured inside the fuel prep section before entering the TE nozzle. The fuel prep section also allowed access for nozzle modifications, fuel line connections, and TE nozzle surface thermocouple attachments. The nozzle was secured to a 2.54 cm thick water-cooled bulkhead flange. Gaseous fuel was delivered to the main fuel manifolds and bulkhead pilot manifold using independently regulated and metered supplies. Commercial grade methane, having the characteristics of natural gas, was supplied by tube trailers.

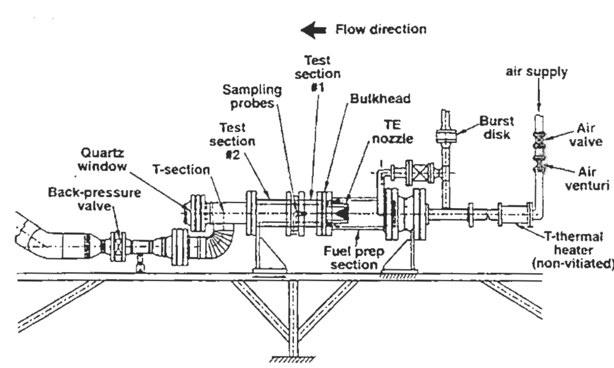


FIGURE 6. SCHEMATIC DIAGRAM OF SNR TEST FACILITY.

Two test sections formed the combustion chamber. The chamber length is defined by the distance from the bulkhead to the gas sampling probes. The assembly of these sections could be varied to achieve combustor lengths of 12.7 cm, 25.4 cm , or 45.7 cm. The 25.4 cm combustor length was commonly used. This provided a 6 ms (combusting) residence time which is characteristic of the engine combustor. Each test section consisted of a cylindrical section of jacketed steel pipe containing a 2.54 cm thick castable ceramic liner, which provided a 15.2 cm ID chamber. The insulating liner was cast from a commercially available ceramic consisting mostly of alumina. The outer jacket was fed with water coolant at a nominal coolant flowrate of 38 liters/min; this provided a usable test apparatus pressure rating of 20 atm. Each test section contained a passage in which a 20-joule spark ignitor was located. Note that no provisions were made to investigate the effect of bulkhead cooling air or liner cooling air on the combustor performance; these activities are conducted in sector rig tests.

A water-cooled instrumentation section containing six emission probes and a static pressure tap was located immediately downstream of the combustion chamber. A second static pressure tap was located on the bulkhead faceplate. (These combustor pressure measurements were nearly identical during all tests.) The probes were positioned at different radii based on equal area segments. The probe inlets were designed (Chiappetta and Colket, 1984) to provide a combination of aerodynamic and thermodynamic quenching in order to rapidly freeze the chemical reactions of CO and NO. Flows through the probes were controlled such that gas samples could be gathered from any combination of probes. Generally, either individual samples or "ganged" samples from all six were acquired.

A transition section (T-section) diverted the flow through two 90 deg turns prior to encountering exhaust coolant water sprays and the back-pressure valve. A window was located in the T-section along the combustion centerline in order to permit observation and recording of the flame patterns. Determination of blowout limits were made on the basis of total and permanent disappearance of flame as the fuel flow was slowly decreased. A remotely controlled back-pressure valve controlled the combustion pressure.

Temperatures, pressures, airflow rates, and fuel flows were measured by conventional transducers, scanners, and flow meters; data were processed by an automatic data acquisition and recording system. Standard gas analysis instruments were used to determine the molar concentrations of CO_2, CO, O_2, UHC, and NOx in the collected sample. The emission data presented herein have been corrected to 15 percent O_2 in a dry sample by using a correction factor (CF):

$$X_i(\text{corrected}) = CF * X_i(\text{measured})$$

where $CF = (0.21-0.15)/(0.21-X_{O2})$
i = CO, UHC, NOx
X_{O2} = mole fraction of oxygen in dried sample

Test Conditions

As noted earlier, the testing reported here was conducted primarily at conditions corresponding to the baseload operating point of the FT8 engine. The test configurations do not account for the combustor liner cooling air or temperature profiling air that may be required for the engine. Therefore, the emissions measured and the flows delivered correspond to those of the primary zone of the combustor. The flows correspond to the total fuel flow and either 65% (TE92 nozzle) or 67.5% (TE93C nozzle) of the combustor airflow. (Our experience has been that secondary air addition has no effect on the measured level of emissions. The dilution effect is accounted for by converting the emission measurements to a fixed percentage of O_2 (15%) in the sample.) Baseload conditions are defined in Table 2:

TABLE 2. FT8 BASELOAD OPERATING CONDITIONS

Inlet Pressure (Pinlet)	19 atm
Inlet Temperature (Tinlet)	740 K
Primary Zone Equivalence Ratio(Phi)	0.51
Primary Zone Flame Temperature (Tflame)	1820 K (2820 F)
Engine Combustion Residence Time	6 ms
Percent Combustor Airflow (TE92)	65%
(TE93C)	67.5%
No Pilot Required	

COMBUSTION TEST RESULTS

The test results reported herein are separated into two sections; the first section reports baseload performance for the TE92 nozzle; and the second section for the TE93C nozzle. Pressure, residence time, inlet fuel/air maldistribution effects on NOx and measured airflow capacity are also presented . While not documented in this paper, tests using various combinations of pilot fuel injection and premixing main gas fuel were conducted in the SNR facility to demonstrate that the designs provide sufficient flame stability and robustness throughout the entire engine operating envelope while maintaining high combustion efficiencies. Documentation of part-power operation is being conducted in a sector rig.

TE92 Nozzle Emissions and Performance

Measured NOx levels for the four different injection schemes are shown in Fig. 7. NOx levels were very sensitive to changes in the penetration both higher and lower than the baseline, medium penetration case and exhibited an exponential dependence with flame temperature. In particular, higher gas fuel penetration with a smaller number of orifices reduced NOx levels to 8 ppm at baseload. This experience was not consistent with the Holdeman criterion probably because the vigorous mixing within the TE nozzle was the dominant mixing process. Lower gas fuel penetration increased NOx levels to 36 ppm. The effect of the 8 times larger number of orifice sites (40 vs 5) of the low penetration configuration was far outweighed by the radial high penetration effect.

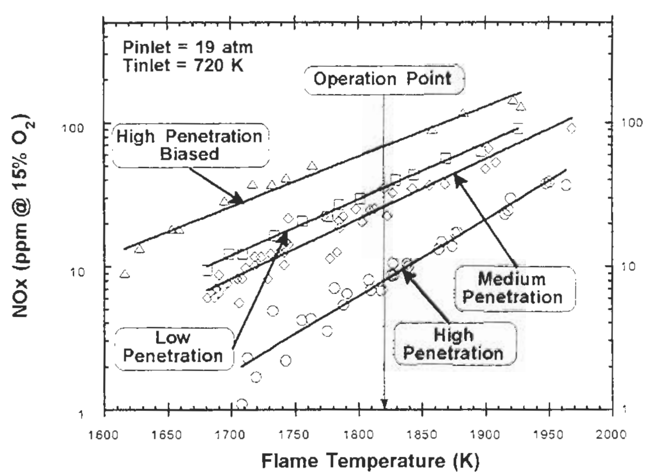


FIGURE 7. TE92 NOX EMISSION DEPENDENCE ON FLAME TEMPERATURE FOR FOUR DIFFERENT ORIFICE CONFIGURATIONS.

Extensive CFD, water flow visualization, airflow velocity measurements, cold flow mixing studies and analytical calculations were made to help understand the effect of injecting gas fuel into a highly swirled airflow generated by the TE geometry. Results indicated that the highest velocity gradients inside the nozzle existed close to the centerbody surface. Injection of fuel into these regions, no matter how coarse, promoted extremely rapid and uniform mixing of the fuel and air by the time the mixture reached the exit plane.

Cone tip temperature measurements acquired during combustion tests indicated temperatures comparable to Tinlet levels for the low and medium penetration cases. However, when the penetration was increased to high levels, cone tip temperatures in excess of 1000 K were experienced as the test conditions were increased from part-power to baseload conditions.

The results of the cold flow studies were examined to ascertain possible causes of high cone tip temperatures. In general, fuel injected at the upstream end of the inlet slot is transported to the axis of the flow path while fuel injected toward the downstream end of the inlet slot remains at the outer periphery of the exiting flow. Velocity measurements verified the anticipated presence of a depressed axial velocity on the flow axis. It was postulated that if even a small fuel flow was supplied to this region, a flame would be stabilized and cause high cone temperatures. The high/bias orifice configuration, designed to prevent fueling of the flow on the axis, did yield low cone tip temperatures at all conditions. However, the NOx levels increased to 70 ppm. Additional testing determined that the cone tip temperature problem was created by the upstream-most orifice in the high penetration orifice configuration. By decreasing the penetration associated with that orifice in the TE92 nozzle, successful robust operation could be achieved.

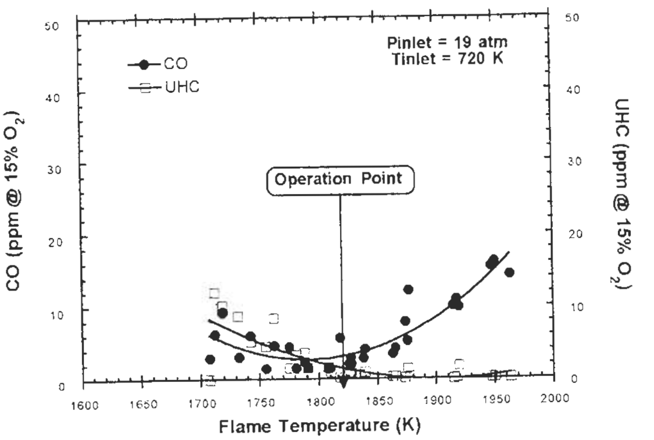


FIGURE 8. CO AND UHC EMISSIONS FOR TE92 HIGH PENETRATION CONFIGURATION.

At baseload conditions, carbon monoxide (CO) and unburned hydrocarbon (UHC) levels for the high penetration configuration were well below 25 ppm over the entire flame temperature range tested, Fig. 8. CO levels increased as the flame temperature was increased above 1800 K, in agreement with calculated CO equilibrium behavior. Efficiencies based upon emission measurements for all four configurations were above 99.99% and remained high until lean blowout (LBO) occurred. LBO for the high penetration configuration occurred at a flame temperature of approximately 1700 K, corresponding to an equivalence ratio of 0.45 (Figs. 7 and 8). This provided a large margin relative to the baseload operation point of 1820 K.

Part power tests were conducted to determine the TE nozzle's range of operation. At baseload, the nozzle operated over a wide flame temperature range on either side of the operation point, providing adequate stability without the need for pilot. At inlet temperatures, pressures and fuel flows corresponding to reduced engine power, small amounts of bulkhead pilot provided adequate combustion stability while maintaining high efficiencies and producing only a small impact on NOx production. Efficiencies of 99.9% were achieved down to 20% power. Reducing the power level to Idle conditions caused the efficiency to fall to 93%. These results were sufficient to demonstrate the ability to sustain efficient operation over the entire FT8 operating range. (Additional developments of the bulkhead pilot are taking place in a sector rig test program.)

The sensitivity of NOx to pressure and residence time were found to be a function of both the level of premixing and the flame temperature, Fig. 9. Both the low and high penetration cases showed a divergence in the NOx levels, for the two pressure levels tested, as the flame temperature was increased. For a high level of premixing (via increasing fuel penetration), the NOx fell below 10 ppm for flame temperatures below approximately 1850 K and was insensitive to pressure changes from 14 atm to 19 atm. However, the lower level of premixing (via low fuel penetration) exhibited sensitivities to pressure even at 1800 K. The negligible NOx sensitivity to pressure over this flame temperature range has been observed in other well pre-mixed systems (Leonard and Stegmaier, 1993) and has been explained by the decreased importance of thermal NOx production at these low flame temperatures (Nicol et al., 1993). As the flame temperature was increased, for the high penetration configuration, above 1850 K, NOx production became a stronger function of pressure which can be explained by the increased role of the thermal NOx production mechanism.

Similarly, the NOx sensitivity to residence time also increased as the flame temperature increased above 1850 K for the low penetration configuration, Fig. 10. At a flame temperature of 1820 K, NOx sensitivities to residence time were small, NOx ~ 0.6*TAU. However, increasing the flame temperature to 1900 K, resulted in a much greater NOx sensitivity to residence time, NOx ~ 4.3*TAU.

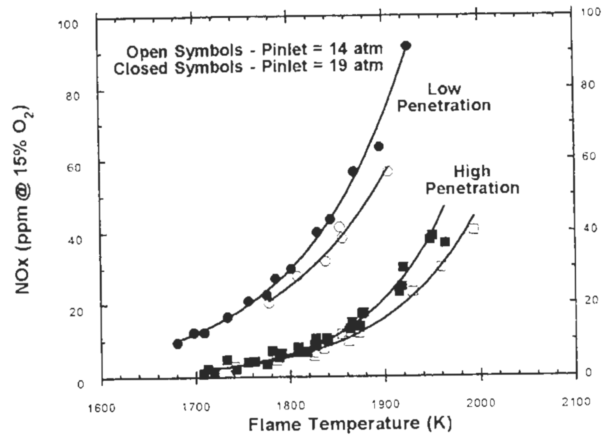


FIGURE 9. TE92 NOX EMISSION DEPENDENCE ON PRESSURE FOR TWO DIFFERENT LEVELS OF PREMIXING.

Again, thermal NOx, which is resident time dependent, plays a strong role at high flame temperatures but only a small role at low flame temperatures.

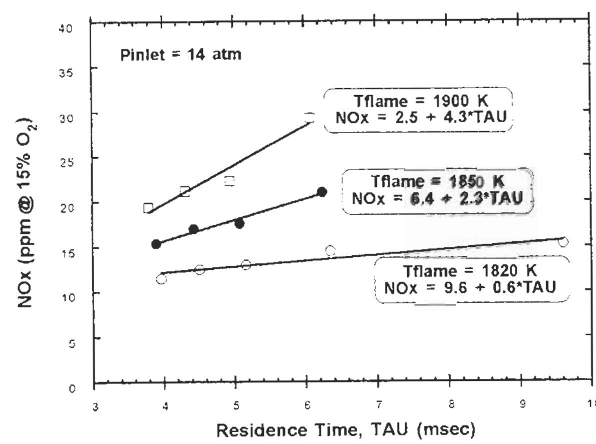


FIGURE 10. NOX DEPENDENCE ON COMBUSTING RESIDENCE TIME (TAU) FOR THE TE92 MEDIUM PENETRATION ORIFICE CONFIGURATION.

NOx sensitivity (using the TE92 high penetration configuration) to the local fuel-air ratio in each inlet was evaluated during a test where the fuel supply to each manifold was controlled separately. This allowed changing the fuel-air ratio in each of the inlets while maintaining the same overall fuel-air ratio (flame temperature). Figure 11 shows the NOx sensitivity to fuel-air ratio changes in inlet slot #1 expressed in terms of the flame temperature that would be achieved upon complete mixing. Large variations in the slot inlet fuel-air ratio, which corresponded to a flame temperature range from 1700 K to 1950 K, produced a negligible influence on NOx. This desired tolerance was consistent with the cold flow results which identified the very high velocity gradients near the cone surface which uniformly mix the fuel and air in the high penetration case. These results suggested that if non-uniform feeding of the inlet slots existed in the engine, as a result of imperfect diffuser performance or unequal fuel-feed, neither flame stability nor NOx production should be affected.

Figure 12 shows the (hot flow) nozzle airflow pressure drop measured during combustion tests for the four different orifice configurations. The average pressure drop was 4%, which was higher than the 3.5% drop predicted using cold flow results. A goal of the TE93C design was to reduce this loss by one percentage point.

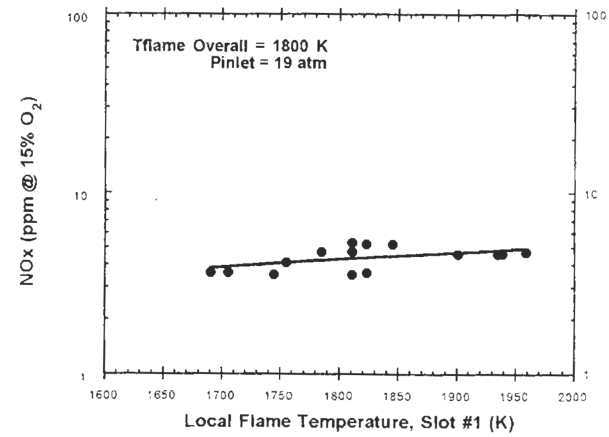


FIGURE 11. TE92 NOX EMISSION DEPENDENCE ON INLET FUEL/AIR MALDISTRIBUTION BETWEEN INLET SLOTS FOR HIGH PENETRATION CONFIGURATION.

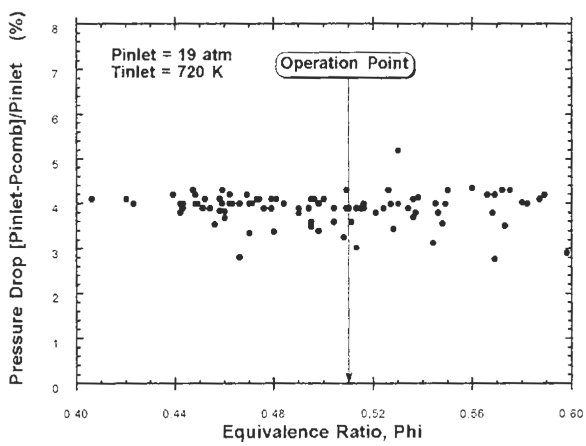


FIGURE 12. TE92 NOZZLE PRESSURE DROP DURING COMBUSTION FOR FOUR DIFFERENT ORIFICE CONFIGURATIONS TESTED.

TE93C Nozzle Emissions and Performance

The TE93C nozzle was first evaluated at baseload conditions using a high penetration orifice array scaled from the TE92 experience. NOx, CO, and UHC emission levels were all similar to those obtained by the TE92 nozzle. Temperatures measured on the cone surface remained low for all operating conditions. During baseload tests, the amount of airflow supplied to the cone was held constant at the design point of 12%.

Reductions in the amount of airflow supplied to the cone were made to determine the robustness of the TE93C's operation at baseload. Suitable valving was installed such that the pressure drop across the cone air flow passage could be reduced relative to the pressure drop across the main air passage. The cone airflow variation achieved as a function of this difference in pressure drop ranged from 12% (no reduction from design) to 8.5% of the total flow, Fig. 13. Over this range, no change in NOx level was observed. This indicated that the cone airflow mixed thoroughly with the main flow prior to the occurrence of combustion. Cone surface temperatures remained low as the cone flowrate was varied. These results indicated that nozzle performance would be quite tolerant to unanticipated cone flowrate excursions.

Airflow capacity obtained from pressure drop measurements during hot testing indicated the TE93C design reduced the air pressure drop to the desired 3% level . Nozzle pressure drop excursions above and below the design operation point of 3% were made to determine possible operational problems while maintaining the design 12% cone flowrate. These excursions were accomplished by modulating the backpressure valve position and the total air

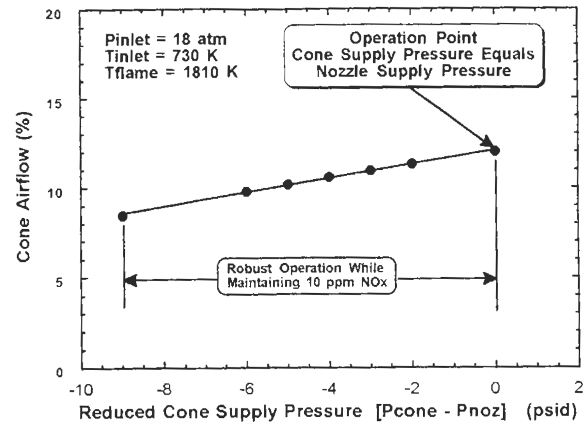


FIGURE 13. TE93C OPERABILITY AND NOX CONTROL MAINTAINED FOR REDUCED CONE AIRFLOW.

flowrate while maintaining the same inlet pressure and inlet temperature. (The inlet pressure was reduced to 13.5 atm for this test series.) The insensitivity of NOx to nozzle pressure drop is shown in Fig. 14. The slightly lower NOx levels at the higher pressure drops are associated with reduced residence times. No flashback or elevated cone temperature problems were experienced over this nozzle pressure drop range. Taken together, the avoidance of operability problems for low nozzle airflow pressure drop and cone flowrates indicated that the TE93C design was a robust, low-NOx producing device meeting the FT8 engine requirements.

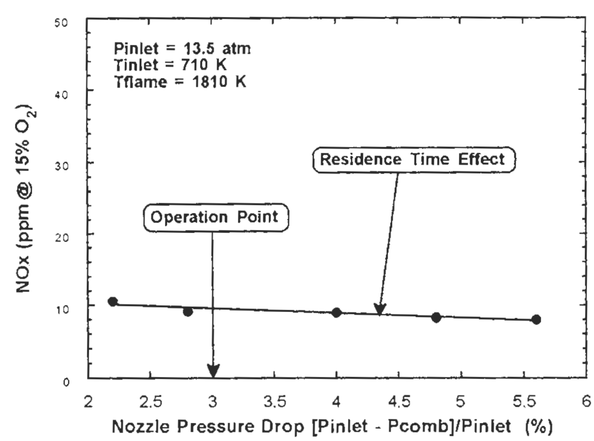


FIGURE 14. TE93C ROBUST, LOW NOX OPERATION PRESERVED OVER WIDE NOZZLE PRESSURE DROP RANGE.

The effect of inlet pressure on NOx emissions was also evaluated for this design. Figure 15 shows the NOx dependence on flame temperature for four different inlet pressures ranging from 5 to 18 atm at a constant inlet temperature and the same residence times. These results indicate some NOx pressure dependence--a generally greater dependence for temperatures higher than 1800 K. The curves converge as the flame temperature is reduced. These results are consistent with the TE92 pressure sensitivity results (Fig. 9).

The independence of NOx level to inlet temperature over the range from 590 to 700 K is shown in Fig. 16. A significant dependence on inlet temperature had previously been observed for different TE92 configurations which exhibited elevated cone tip temperatures; this suggested combustion was taking place in the cone tip wake where high fuel concentrations were present. The NOx insensitivity to inlet temperature for the TE93C design is consistent with the elimination of any combustion inside the nozzle or diffusion flame combustion. Both cone tip temperature measurements and surface temperature measurements at the nozzle exit have indicated no signs of flame propagation into the nozzle, even when the TE93C is operated at off-design conditions.

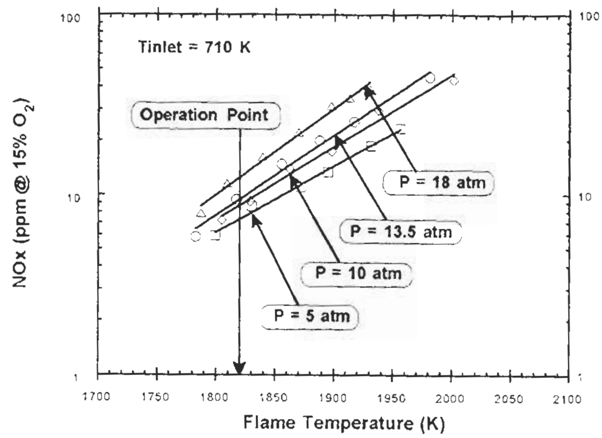


FIGURE 15. TE93C NOX EMISSION DEPENDENCE ON FLAME TEMPERATURE FOR FOUR DIFFERENT INLET PRESSURES.

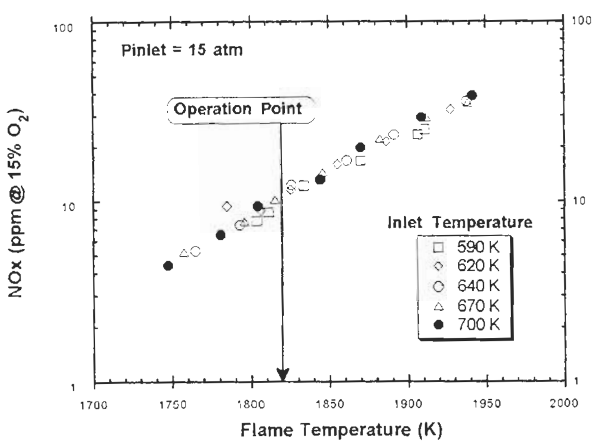


FIGURE 16. TE93C NOX EMISSION DEPENDENCE ON FLAME TEMPERATURE FOR FIVE DIFFERENT INLET TEMPERATURES.

CONCLUSIONS

1) NOx levels well below 25 ppm are achievable in moderate pressure ratio aeroderivative engines using a reasonable number of simple, rugged, high-air-flow capacity, high-swirl, tangential entry fuel injectors.

2) NOx performance is sensitive to the extent to which the fuel jets penetrate into the scroll flow. A large number of injection sites is not required; five high penetration sites per inlet produced the desired NOx control. Penetration of fuel to the centerbody surface can lead to high NOx levels and operability problems. Use of a counter-swirling centerbody air flow and a reduced fuel penetration of the upstream-most orifice effectively eliminates operability problems.

3) NOx performance should be insensitive to diffuser flow non-uniformities.

4) NOx performance and operability for these nozzles is insensitive to nozzle pressure drop down to 2% and inlet air temperatures ranging from 590 to 700 K..

5) The NOx performance signature for a given design can be confidently expressed as an exponential function of the flame temperature derived from the primary zone fuel-air ratio. Careful control of primary zone stoichiometry in the engine is a prerequesite for low NOx engine performance.

6. NOx sensitivities to pressure and residence time were found to be small at flame temperatures below 1850 K. Above 1850 K some NOx sensitivity to pressure and residence time was observed and was associated with the increased role of the thermal NOx production mechanism at elevated flame temperatures.

RECOMMENDATION

The slight dependence of NOx levels on pressure and residence time suggest that the fuel-air mixture produced by these devices is well mixed, but not perfectly mixed. Further reductions in NOx levels are probably achievable through refinement of the injector orifice array. Cold flow studies should be conducted to evaluate the extent of mixture uniformity improvement that can be achieved.

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