Full Annular Rig Development of the FT8 Gas Turbine Combustor

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ABSTRACT

The results of developmental testing in a high pressure, full annular combustion section of the FT8 industrial gas turbine are presented. Base power conditions were simulated at approximately 60% of burner pressure. All aspects of combustion performance with liquid fuel were investigated, including starting, blowout, exit temperature signature, emissions, smoke and liner wall temperature. Configurational changes were made to improve liner cooling, reduce emissions, adjust pressure loss and modify exit temperature profile. The effects of water injection on emissions and performance were evaluated in the final test run. Satisfactory performance in all areas was demonstrated with further refinements to be carried out during developmental engine testing.

NOMENCLATURE

ALP  Air Loading Parameter
b,c  Constant in ALP equation
CO  Carbon monoxide
ER  Equivalence ratio, fuel-air/stoichiometric fuel-air
LBO  Lean blowout fuel-air ratio
NOx  Oxides of nitrogen
FF  Pattern factor, non dimensional peak exit gas temperature (equation 3)
ppm  parts per million by volume
Pin  Burner section inlet pressure, psia
Rnox  Ratio of wet NOx to dry NOx
SN  SAE smoke number
Tim  Burner section inlet temperature, °R
V  Burner volume, cubic feet
VBR  Von Brand Reflectance
Wa  Burner section air flow, pps
Wf  Fuel flow, ppb
W/F  Water to fuel ratio

INTRODUCTION

The FT8 industrial/marine gas turbine is currently under development for introduction into service by late 1990. Although this gas turbine is a derivative of the widely used JT8D aircraft jet engine, the combustion system will have significantly different operational requirements. A new fuel injector, capable of employing either liquid or gaseous fuels, water or steam injection for NOx control or any combination thereof has been under development in a single segment rig (Reference 1). The basic JT8D combustion chamber was modified to accept the larger new injector.

Prior to introduction into an actual FT8 engine, further testing was required in a full annular combustor rig to verify measurements made in the single segment rig and develop combustor performance qualities such as exit temperature signature and flame propagation which are not measurable in a single segment rig. Like the JT8D, the FT8 combustion system has nine fuel injectors and nine individual can type combustors situated in an annular combustion case. The full annular rig as described in the following section fully simulated this arrangement as well as all the geometry and aerodynamics of the combustion section from the diffuser inlet to the burner exit. The test program was accomplished in four runs. Use of split configurations (four adjacent combustors of one configuration and five of another) in the final three tests allowed a total of seven configurations to be evaluated.

Although the full annular rig is primarily a tool for exit temperature signature development, opportunity was taken to modify the burner front end combustion airflow addition schedule for reduced NOx emissions. Due to the lack of gas fuel storage and handling facilities at the test stand, only liquid fuel and water were evaluated.

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TEST FACILITY

The test facility, described schematically in Figure 1, has high pressure airflow supplied to the inlet by two series mounted compressors driven by an FT4A gas turbine. Rig inlet air is preheated to combustor inlet conditions in two indirectly fired, non-vitiating preheaters operating in parallel. Airflow capacity of up to 45.5 kilograms/second (100 pps) with inlet temperatures and pressures up to 923°K (1200°F) and 4.14 MPa (600 psia) respectively, is available.

RIG PRESSURE CAPSULE TRAVERSE
EXHAUST
LET TRANSITION DUCT
RIG TRAVERSE RAKE BODY
TRAV EL RAKE HEAD
FIGURE 1. HIGH PRESSURE COMBUSTION TEST FACILITY

Redundant airflow measurements are made both upstream and downstream of the preheaters. The primary measurement is made upstream of each preheater with a pair of sonic orifices with measurement accuracy of within 0.5 percent. The test section is installed in a breech locked tank which is pressurized above rig operating pressure to minimize burst loads. The rig inlet air duct provides an accelerating flow field in the transition from cylindrical to annular cross-section.

The rig test section itself is comprised of full annular diffuser and burner cases in which are mounted nine fuel injectors and nine can combustors. The rear end of each combustor fits into a porthole in the face of an annular transition duct. Calibrated holes at the rear of the burner case allow shroud air to bypass the burner at a rate equal to the engine turbine cooling air requirements.

The fuel system consists of a single fuel feed pipe which feeds a single flow divider. This valve has nine ports, supplying nine fuel manifolds, one to feed each fuel nozzle.

Circumferentially traversing combustor discharge rakes are mounted on a shaft rotating about the centerline of the combustor annulus. The traverse shaft extends through the rear wall of the exhaust chamber and is turned by an externally mounted actuator.

The pressure level in the test rig is regulated by a water cooled back pressure valve. Combustion exhaust gas is quenched by a water spray prior to atmospheric discharge through a silencer pit.

The data acquisition system incorporates, in addition to the standard pressure and temperature instrumentation, instrumentation for emissions and smoke measurements consistent with those specified by the latest EPA requirements. Steam-traced emission sampling lines are routed to the emission console located in the control room, where they can be manifolded as required.

INSTRUMENTATION

Figure 2 shows the fixed diffuser and burner case instrumentation. Three multi-head Kiel type total pressure rakes and two multi-head total temperature rakes are spaced circumferentially at the diffuser inlet. Each rake has four radially spaced sensors. Burner case static pressures are located at five axial positions along the inner case and four axial locations along the outer case. At each of these locations probes are located at three circumferential positions.

Kiel type total pressure probes are located at three circumferential positions at the rear of both cases. Static pressure taps are situated at the exit of the bypass air bleed holes to calculate the simulated turbine cooling air flow.

In order to detect lightoffs and blowouts, a total of 18 thermocouples, two per fuel injector are installed in the wall of the transition duct.

Exit temperature measurements are made with two multi-head rakes mounted on the rotating traverse. These were composed of six radially spaced thermocouples each. Similarly, exit pressure measurements and exhaust smoke and emissions sampling were accomplished by a multi-head rake comprised of four Kiel type heads mounted on the rotating traverse mechanism.

A Kulite type sensing probe was inserted into the burner case to measure pressure oscillations.

FIGURE 2. FULL ANNULAR COMBUSTION SECTION WITH INSTRUMENTATION
TEST PROGRAM

Hardware

The production dual fuel nozzle as shown in Figure 3 is externally a more compact version of the experimental nozzle described in Reference 1, but employs the same fuel injection philosophy. The liquid fuel is atomized by the air blast method whereby a swirling thin liquid film encounters high velocity airflow on either side. This system produces a good circumferential spray pattern, even at low pressure drop, and allows for the large turndown ratio necessary when water injection for NOx control is passed through the same passage. Swirl is induced in both inner and outer air passages by angled vanes. Gaseous fuel injection would ordinarily take place from slots in the exit of an annular passage wrapped around the liquid fuel nozzle. The nozzle used in the annular rig was devoid of this feature for ease of manufacturing early in the program since gas was not employed in this test series.

![Figure 3. Dual Fuel Injector (Gas System Not Incorporated in Full Annular Rig Injector)](https://proceedings.asmedigitalcollection.asme.org/doi/abs/10.1115/GT2018-76847)

The initial combustor configuration was a basic JT8D reduced emissions can-type combustion chamber modified to accept the larger diameter of the dual fuel injector, as in the single segment rig testing. The initial combustor airflow addition schedule was similar to that of the JT8D reduced emissions combustor which had been optimized for low idle emissions with its hybrid fuel injector (Reference 2). The industrial engine goal of reduced NOx at high power required a new airflow addition optimization which was pursued in the present test program through modifications to the combustor hole pattern. After the initial baseline test of scheme 2A, schemes 4C through 9D were tested at the rate of 2 configurations per run while adjustments were made for pressure loss, exit temperature profile, cooling flow and NOx emissions as listed in Table I. The axial airflow distributions are presented in Figures 4 and 5.

![Figure 4. Compressor Airflow Distribution](https://proceedings.asmedigitalcollection.asme.org/doi/abs/10.1115/GT2018-76847)

![Figure 5. Compressor Airflow Distribution](https://proceedings.asmedigitalcollection.asme.org/doi/abs/10.1115/GT2018-76847)

Fuel

Standard Jet A aviation fuel was readily available at the test site and was employed throughout the program. Although this fuel is somewhat more volatile than the diesel fuel used in industrial gas turbines, both the literature (Reference 3) and our single segment rig testing had indicated that the differences would be small. Diesel fuel would be expected to produce slightly higher smoke and NOx and to require longer starting time. There should be no effect on exit temperature profile.

### Table I

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Scheme</th>
<th>NOx Reduction</th>
<th>Exit Temp.</th>
<th>Cooling Profile</th>
<th>Pressure Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2A</td>
<td>---------------</td>
<td>BASELINE</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>4C</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>6D</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>8D</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>9D</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

The axial airflow distributions are presented in Figures 4 and 5.
Test Conditions

Data was acquired at starting, snap decelerations (decel) and simulated base power conditions. The start and decel points are representative of steady state points along engine transients and fully simulate the engine temperature, pressure and airflow at the burner inlet. The blowout testing (Table II) was performed over a range of air loading parameters (ALP) to define a blowout boundary. The facility had an airflow limitation below that of the engine, therefore the base (100%) power point had to be simulated by duplicating burner inlet and exit temperatures and burner inlet flow parameter. The simulated conditions for base power are given in Table II.

<table>
<thead>
<tr>
<th>TABLE II FULL ANNULAR RIG OPERATING POINTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Start</td>
</tr>
<tr>
<td>LBO</td>
</tr>
<tr>
<td>LBO</td>
</tr>
<tr>
<td>LBO</td>
</tr>
<tr>
<td>LBO</td>
</tr>
<tr>
<td>Base</td>
</tr>
</tbody>
</table>

COMBUSTOR DEVELOPMENT

Starting and Propagation

Both starting and flame propagation were relatively fast for an industrial engine. Thermocouples behind each burner can indicated a three second elapsed time between fuel entering the combustors and the initial light-off. Flame propagation took another 0.2 to 4.5 seconds. The starting and propagation time was independent of fuel flow rate over the range tested.

Section Pressure Loss

Target section pressure loss was 6% of burner inlet pressure (Pin). The initial test configuration produced a section pressure loss within 0.1% Pin of the target. However, inspection of the exit temperature isotherms indicated spikes of cold air at both span edges. These spikes were traced to leakage between the burner aft end seals. The leakage was corrected for the final three runs. With minor modifications in each run the final configuration was 0.15% Pin above goal. This left some margin for future modifications to the cooling flow in engine development without having to compensate by adjusting the combustion and dilution holes.

Lean Blowout

Lean blowout (LBO) is the fuel-air ratio below which combustion cannot be sustained for a given burner inlet condition. LBO data is generally correlated against a combustor air loading parameter (ALP) such as that suggested by Lefebvre and Greenbough (Reference 4):

\[ \text{ALP} = \frac{e \cdot W_a}{P_{in}^{1.8} V \cdot e^{2.3 \cdot v_b}} \]  

The authors state that the factor e is a function of combustor equivalence ratio, but in practice the local stoichiometry in the flame stabilization region is not known so that e is set to a constant. Blowout occurrences in the full annular rig are measured with the same exit thermocouples behind each combustor as employed as startup indicators. Data for the last two runs is plotted versus the air loading parameter in Figure 6. The difference between the two runs is negligible. Run 2 LBO data, not shown, was 10% higher than runs 3 and 4. That configuration had a high pressure loss which would have increased front end air flow sufficiently to explain the discrepancy. Comparison of the final run (run 4) data versus the calculated engine drop load decel path indicates sufficient margin exists to prevent combustor blowout.

Exit Temperature Profile and Pattern Factor

An intentional effort to adjust the exit temperature profile was made only in the final run. Adjustments of front end air flow made in runs 2 and 3 for emissions reductions had significant effects on the exit profile. The baseline scheme 2A configuration had a profile which peaked in the outer span (73-88% span) as shown in Figure 7. Profile factor is defined as:

\[ \text{PROFILE FACTOR} = \frac{T_{\text{MAX AVG}} - T_{\text{AVG}}}{T_{\text{AVG}} - T_{\text{IN}}} \]  

FIGURE 6. FULL ANNULAR RIG LEAN BLOWOUT VERSUS AIR LOADING PARAMETER

FIGURE 7. COMPARISON OF EXIT TEMPERATURE RADIAL PROFILES
The successful front end combustion hole adjustment which resulted in reduced NOx scheme 6D of run 3 shifted the profile peak to the inner (24%) span. Adjustment of the combustion rear end dilution hole pattern was made for scheme 8D to shift the profile to the outer span as shown in Figure 8 versus the target profile. The match was considered more than acceptable for initial engine testing. Water injection had little effect on the exit profile. Figure 9 compares the scheme 8D profile dry and at water to fuel ratios of 0.5, 1.0 and 1.5. They are essentially the same.

\[ PF = \frac{T_{\text{MAX}} - T_{\text{AVG}}}{T_{\text{AVG}} - T_{\text{IN}}} \quad (3) \]

Like the profile, the pattern factor was affected by front end air flow. Scheme 6D, which shifted the profile toward the inner diameter also reduced the pattern factor by 0.09 relative to the baseline. The final configuration, scheme 8D had an acceptable pattern factor that was only 0.01 lower than the baseline. Apparently the very low pattern factor of scheme 6D was associated with the inner peaked profile. The pattern factors for the various combustor configurations are summarized in Figure 10.

As with profile factor, water injection had no effect on pattern factor indicating that the combustion dilution hole pattern obtained for dry running is also suitable for wet application.

Emissions

Industrial gas turbines must meet strict NOx emissions regulations while controlling unburned hydrocarbons and carbon monoxide. When water injection is employed as the NOx control method, the combustor must have a relatively low dry NOx level and an effective reduction (Rnox) at a given water/fuel ratio. The initial test showed the dry NOx level of the baseline scheme to be too high at 325 ppm (all emissions levels reported are on a dry basis corrected to 15% oxygen) at simulated base power condition. When corrected to actual engine pressure by the standard factor of Pin, a dry NOx level of approximately 425 ppm would be expected. The high NOx level of the baseline configuration was not entirely unexpected because of the significant difference in performance requirements, and fuel injection technique between the JT8D, from which the baseline was derived, and the FT8.

An analysis of the fuel-air schedule for the initial scheme 2A combustor showed that at base power, an equivalence ratio between 0.8 and 1.2 was maintained for a considerable length of the combustor, as shown in Figure 11. This combination of long residence time at high temperature promotes NOx formation.

Subsequent schemes were devised to add quench air at the end of the primary zone to reduce the time spent at high temperature. This technique was generally successful. For example, schemes 6D and 8D (identical except for dilution holes) which followed the quick quench stoichiometric schedule also shown in Figure 11, had measured NOx levels of 243 and 239 ppm respectively, a reduction of 26% from the 2A baseline. Scaling for pressure to actual engine base power produces an estimated 315 ppm of NOx. This was within published levels for other aeroderivative engines of the FT8 class (Reference 5).

While the simple one-dimensional analysis of combustor stoichiometry shown in Figure 11 was useful in obtaining significant NOx reductions, the limitations of this type of analysis were demonstrated by scheme 9D where NOx levels were 50 ppm higher than scheme 8D despite additional mid-combustor air addition. It is surmised that the additional air over-penetrated the two-dimensional mid-combustor flame zone or else recirculated back into the primary.

Water injection testing with the scheme 8D demonstrated excellent NOx reduction efficiency. Rnox shown in Figure 12 is consistent with published data (Reference 6).
Carbon monoxide and unburned hydrocarbons were not a problem with water injection. Hydrocarbons never rose above 3.6 ppm. Carbon monoxide was less than 15 ppm below a 1.2 water/fuel ratio increasing to 54 ppm at a 1.5 water/fuel ratio. At the 1.2 ratio NOx was less than 30 ppm even after correcting for pressure while an acceptable CO level of 15 was maintained. The effect of increased pressure at actual engine conditions would be to reduce the measured levels of both hydrocarbons and carbon monoxide.

The effect of water addition on smoke levels is shown in Figure 13 where smoke number is shown versus water/fuel ratio for schemes 8D and 9D. Smoke decreases to very low levels at water/fuel ratios above 1.0. It can be concluded that if dry smoke levels are satisfactory, wet levels will be even more so.

Industrial engine smoke requirements are typically quoted in Von Brand Reflectance (VBR) units where 100 VBR is perfectly clean and 0 is perfectly black. The relationship between SAE and VBR smoke levels is described in Figure 14. An SAE 13 smoke level is approximately 95 VBR. Although smoke visibility depends on many factors, the smoke demonstrated by schemes 8D and 9D should be invisible.

No pressure correction to actual engine conditions was made since none was indicated by testing in full pressure single segment rig testing. Smoke regulations are enforced at the exhaust stack rather than the burner exit. Clean air from turbine cooling added between the burner exit and the stack should reduce smoke sufficiently to compensate for the increasing smoke effect of diesel fuel relative to Jet A.

Smoke

Smoke data were acquired by means of a sampling traverse at the combustor exit. The dry smoke number (SAE units) for the initial scheme 2A and the final two configurations, 8D and 9D, of run 4 are listed in Table III:

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Scheme</th>
<th>SAE SMOKE NO.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2A</td>
<td>13.2</td>
</tr>
<tr>
<td>4</td>
<td>6D</td>
<td>9.5</td>
</tr>
<tr>
<td>4</td>
<td>9D</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Schemes 8D and 9D had progressively more mid-combustor air addition for NOx reduction relative to the 2A baseline and the trend of decreasing smoke indicated that these modifications were also beneficial to smoke.
Burner Efficiency

In dry operation, the FT8 combustor system operated at over 99.9% burner efficiency at all high power conditions. This level was retained even up to 1.5 water/fuel ratio on wet operation. Burner efficiency was lower during idle operation, as expected. Measurements made during run 3 indicated a 96.5% level for scheme 6D which has the same front end as the 8D. This level is considered satisfactory since it should be sufficient to prevent visible "white smoke" often seen in the exhaust at these conditions.

Liner Durability

Combustor cans of each configuration were coated with temperature sensitive paint on both the hot and cold surfaces to assess wall temperatures and potential durability. Thermal barrier coating which is bill-of-material on production combustors was not employed on the test cans.

On the basis of the paint results, cooling patterns evolved from the "A" to "C" to "D" schemes and liner hot spots were eliminated. Adding front end air for NOx quenching cooled the rear liner walls as flame temperature decreased. In some configurations (5C and 7D) where the front end hole pattern was more radically altered, new hot spots appeared which would have required further development had these configurations shown promise as low NOx candidates.

Burner Noise

Combustor noise levels that increase with increasing water injection rates and increasing fuel-air ratios have been reported in the literature (Reference 7). These trends were observed in the full annular rig by instrument and human ear. Levels of concern were observed only for water-fuel ratios above 1.5. Experience has shown that stand geometry, specifically the length of the exhaust duct, has an influence on resonant frequencies such that rig generated noise may not appear in the engine. Combustor noise will be fully monitored in engine water injection tests.

CONCLUSIONS

A combustor configuration (scheme 8D) was developed in the full annular rig which fully satisfied all goals for initial engine testing with liquid fuel and water for NOx abatement. Dry NOx emissions were reduced by 26% from the initial configuration. Target exit temperature signatures and section pressure loss were obtained. Adequate starting characteristics, blowout, smoke and potential liner durability were demonstrated. Both dry NOx and NOx reduction effectiveness with water should produce competitive NOx levels. Water injection reduced smoke levels and had no effect on exit temperature pattern.

REFERENCES


