Experimental Evaluation of a Liquid-Fueled, Lean-Premixed Gas Turbine Combustor

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ABSTRACT

Rig testing of a lean-premixed, liquid-fueled combustor was conducted to establish the feasibility of achieving ultra-low NOx emissions at typical gas turbine operating conditions. Two different filming fuel injector concepts were evaluated.

The majority of combustor testing was conducted using No. 2 diesel. The test results showed 12 and 20 ppm NOx at 6 and 9 atm, respectively. Corresponding CO levels were 50 ppm in both cases.

INTRODUCTION

Broadly speaking, gas turbine NOx emissions can be controlled to two levels. "Low" NOx is characterized by emissions on the order of 25 to 50 ppm (corrected to 15% O2) and can be achieved through water or steam injection. "Ultra-low" NOx includes emissions below 25 ppm and more generally pertains to levels near 9 ppm. SCR is currently the only commercial technology capable of reducing NOx emissions to ultra-low levels.

The work described below represents a first step in the development of a liquid-fueled gas turbine combustor capable of achieving ultra-low NOx levels without water injection or SCR. The use of lean-premixed combustion for "dry" NOx control avoids the technical problems and high costs associated with these other control methods.

The ultra-low NOx combustor concept being developed uses lean-premixed/prevaporized combustion to limit NOx emissions. Emissions are reduced by operating the burner primary zone at a leaner fuel/air ratio than is typical. In addition, premixing reduces fuel/air mixture inhomogeneities that can cause locally high gas temperatures that can contribute significantly to NOx emissions.

PROGRAM OVERVIEW

The study involved the experimental assessment of two filming fuel injector configurations to document the feasibility of achieving ultra-low NOx emissions through lean-premixed/prevaporized combustion. The program focussed on firing No. 2 diesel fuel, the predominant liquid fuel for industrial gas turbines. Limited testing was conducted using JP-4 to assess emissions with a more easily vaporized fuel.

Earlier studies had documented the ability to achieve ultra-low NOx emissions with lean-premixed combustion when firing natural gas (Smith, 1987a; 1987b).

The liquid fuel injectors evaluated were designed to be compatible with a cylindrical combustor used in the earlier natural gas studies. The major goal of the testing was to demonstrate ultra-low NOx emissions and low CO emissions (50 ppm at 15% O2) on No. 2 diesel (Table 1).

TABLE 1. NOMINAL DESIGN POINT OPERATING CONDITIONS

<table>
<thead>
<tr>
<th>Output</th>
<th>3700 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustor pressure</td>
<td>9.1 atm</td>
</tr>
<tr>
<td>Combustor inlet temperature</td>
<td>620°F</td>
</tr>
<tr>
<td>Turbine inlet temperature</td>
<td>1850°F</td>
</tr>
</tbody>
</table>

COMBUSTION SYSTEM DESCRIPTION

The ultra-low NOx combustor assembly is illustrated in Figure 1 and includes the primary air swirler, fuel injector, and combustor liner. Key features of these components are described below.

Primary Air Swirler

An eighteen vane, radial inflow swirler was used to impart a high degree of swirl to the primary combustion air. This swirl served two purposes. First, the swirl aided in fuel/air premixing as described in detail below. In addition, the swirling flow stabilized the combustion process in the burner. The vortex motion in the primary zone recirculated combustion products back upstream along the combustor axis thus providing an ignition source for the incoming fuel/air mixture.

The swirler/fuel injector subassembly is shown in Figure 2. The swirler vane angle was adjustable to permit control of the degree of primary air swirl. The vane angle was set to yield a flow swirl angle of 44 degrees into the burner primary zone. This matched the conditions tested previously using natural gas.
Construction was of Hastelloy X sheet metal of 0.040 inch thickness. To maintain acceptable liner temperatures, the burner was film cooled. The combustor dome incorporated eight radial cooling strips. A total of ten circumferential cooling strips were located at equally spaced intervals along the combustor axis.

Fuel Injectors

The fuel injector/air swirler subassembly was designed to permit three different modes of liquid fuel injection. The two injection modes evaluated in the study were designated as "inner" and "outer" filming and are illustrated in Figure 3. A pilot fuel injection capability was also included to simplify combustor lightoff.

Inner filming involves filming of the liquid fuel on the cylindrical swirler centerbody. The fuel film is carried downstream to the primary zone by the swirling primary air flow. The fuel vaporizes and premixes as the film progresses along the centerbody. In practice, insufficient residence time exists in the swirler channel to allow fuels with low vapor pressure fractions such as No. 2 diesel to prevaporize completely. Thus, an air-assist/air-blast capability is incorporated in the centerbody design. This secondary air stream exits from the centerbody downstream face through an annular gap just inside the centerbody lip. The secondary air-assist/air-blast stream acts to break up any remaining fuel film as it flows off the centerbody and into the primary zone.

The inner filming concept had been demonstrated successfully earlier in work which explored using methanol as a gas turbine fuel (Smith, 1983). The inner filming approach assessed in the current program represents an extension of the concept to heavier fuels.

For inner filming, fuel is delivered to the surface of the centerbody through eight orifices located around the centerbody circumference. The orifices are located a distance of five inches from the downstream lip of the centerbody.

The outer filming concept involves film formation on the outer cylindrical surface of the air swirler channel. Fuel is delivered to the filming surface in a manner identical to that used for inner filming. Provision is also made for air-assist/air-blast of the outer fuel film at the exit of the swirler channel.

The justification for testing the outer filming concept was its larger surface area for vaporization than the inner film. In addition, the outer fuel film would tend to be more stable than the inner film due to centrifugal effects. With the inner filming concept, centrifugal forces would tend to destabilize the film with fuel droplets and ligaments possibly being shed into the swirler air flow.

During the fuel injector design, it was recognized that the stripping of droplets from the inner film could significantly augment fuel vaporization and premixing by dispersing droplets across the swirler channel. Testing was intended to establish whether the larger, more stable outer film provided any combustor performance advantage over the possible random droplet shedding phenomenon of the inner filming concept. In addition, the combustor test facility was sufficiently flexible to allow both the inner and outer filming injectors to be operated simultaneously.

TEST RIG DESCRIPTION

The combustor test rig is illustrated in Figure 4. Instrumentation was available to determine air and fuel flow rates, inlet air temperature and pressure, combustor wall temperatures, combustor pressure drop,
COMBUSTOR PRIMARY ZONE

INNER FILM
INNER AIR
ASSIST/AIR
BLAST
PILOT
FUEL

PRIMARLY AIR
OUTER AIR
ASSIST/AIR
BLAST

FIG. 3 - VARIABLE FUEL INJECTION MODES

TABLE 2. LOW NOx COMBUSTOR FLOW DISTRIBUTION

<table>
<thead>
<tr>
<th></th>
<th>Effective (in.²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swirler</td>
<td>2.029</td>
</tr>
<tr>
<td>Liner Cooling</td>
<td>1.310</td>
</tr>
<tr>
<td>Inner Air Assist Port</td>
<td>0.195</td>
</tr>
<tr>
<td>Outer Air Assist Port</td>
<td>0.126</td>
</tr>
<tr>
<td>Total</td>
<td>3.660</td>
</tr>
</tbody>
</table>

COLD FLOW TEST RESULTS

A vacuum flow rig was used to determine the overall pressure drop and flow split characteristics of the combustor assembly. Table 2 presents the combustor flow distribution test results.

To assess fuel injector performance qualitatively prior to combustor testing, the inner filming fuel injector was installed in a flow visualization rig. The atmospheric pressure test rig included the radial swirler assembly mounted within an air plenum, the inner filming fuel injector, and a clear quartz tube that replaced the outer cylinder of the fuel/air mixing passage. Water was used as a test liquid. The intent of the flow visualization study was to determine the operating conditions under which a uniform, continuous liquid film was formed on the surface of the cylindrical injector body.

The primary parameter varied during the flow visualization study was air velocity in the swirler premixing channel. For convenience, air velocity changes were monitored by altering the swirler pressure drop ratio (DP/P).

The filming injector was viewed over a range of DP/P from 2.0 to 4.0%. The photographs in figures 5 and 6 show that the film distribution on the injector centerbody becomes more uniform as pressure drop (and air velocity) is increased. At a DP/P less than about 2.5%, the liquid film is not sustained over the length of the injector. Rather, after leaving the fuel orifices, the liquid forms a thick rivulet, swirls to the bottom of the injector, and travels as a thick stream to the end of the injector (Figure 5). This behavior reflects the dominance of gravitational over shear forces in the horizontal orientation of the test configuration.

FIG. 5 - LIQUID FILM DEVELOPED AT AN AIR SWIRLER DP/P LESS THAN 2.5%

As combustor pressure drop ratio is increased, the film becomes thinner and more evenly distributed around and along the injector (Figure 6). At even higher DP/P
COMBUSTOR PERFORMANCE TESTS

Combustor performance testing was conducted in three phases. Initially, inner and outer filming were assessed separately. Then combustor performance with combined inner and outer filming was examined.

Inner Filming Injector Performance

The initial inner filming injector tests were conducted using air-blast rather than air-assist to augment film vaporization. Air-blast refers to fuel atomization by a secondary air flow that results solely from the combustor pressure drop. This is accomplished by allowing combustor inlet air to flow through the injector centerbody air-assist passage. The air-blast flow is at the combustor inlet air temperature. Flow rate depends on combustor pressure drop and the open area of the air-assist passageway.

Air-assist refers to the introduction of air through the air-assist passage from a separate air source that is higher in pressure than the combustor inlet air. For the tests conducted in this program, air used for air-assist was at ambient temperature in contrast to the high temperature flow used for air-blast. The impact on burner performance of using a cold air-assist flow is uncertain. The low temperature of the air used for fuel atomization and the lower injector hardware temperature act to slow the vaporization process. This would tend to increase NOx emissions while decreasing CO levels. On the other hand, injecting cold air into the combustor acts to decrease flame temperature which can have exactly the opposite effects on NOx and CO concentrations.

Figure 7 shows the NOx and CO emissions of the inner filming injector using only air-blast. Tests data at 6 and 10 atm are shown. The NOx results show the classical lean premixed characteristics. NOx emissions decrease with decreased fuel-air ratio (flame temperature decreases) and increase with pressure (higher reaction rates). CO emissions remain low until the lean flammability limit is approached. CO levels then increase rapidly with decreased fuel-air ratio. At 10 atm NOx levels were near 40 ppm with CO at 50 ppm. At 6 atm, NOx levels dropped to about 25 ppm with 50 ppm CO.

Visually the flames in these tests appeared to be primarily of the blue, premixed type, but near the swirler centerbody a yellow flame zone could be seen. As combustor pressure was increased, the flame became more luminous with brighter yellow tinges. The observations indicate that some fraction of the fuel flow was reaching the primary zone as a liquid from the injector centerbody surface.

An evaluation of the impact of air-assist on emissions was also conducted with the inner fueling injector. Test results at 6 atm are shown in Figure 8. Air-assist level is shown as a ratio of air-assist air flow to fuel flow. The data show a moderate reduction in NOx emissions with increased air-assist but a concurrent small degradation in CO emissions. Figure 8 indicates that NOx levels near 17 ppm were achieved with CO levels at 50 ppm at the highest air-assist level tested.

Outer Filming Fuel Injector Performance

Figure 9 compares the combustor emissions resulting from inner and outer filming injector operation (using air-blast) at a combustor pressure of 6 atm. At a fuel-air ratio yielding 50 ppm CO, outer filming yielded NOx emissions near 50 ppm which was nearly double that of the inner filming injector.

Visually the flame resulting from outer filming displayed high luminosity indicating a reduced level of prevaporization. Apparently the tendency of the inner filming injector to disperse droplets across the swirler...
Premixing channel aided prevaporization and premixing more than the added surface area of the outer filming configuration. In contrast to the inner filming flame which stabilized on the injector centerbody, the outer filming flame stabilized on the swirler channel outer wall since this was the location of fuel entry into the combustion zone.

Additional testing of the outer filming injector was conducted to explore the role of air-assist in improving emissions. The test data indicate that increasing levels of air-assist do not reduce NOx emissions significantly although CO levels increased moderately.

**Combined Inner and Outer Filming Fuel Injection**

Combustor performance with simultaneous fueling through both the inner and outer filming fuel orifices was also evaluated. Simultaneous fueling should maximize the fuel film surface area and fuel vaporization rate. In turn, this should increase the rate of fuel-air premixing and have a positive effect on combustor emissions.

Typical test results at 6 atm using only air-blast augmentation are presented in Figure 10. Curves are shown for varying fractions of inner and outer fueling presented as the ratio of inner fuel to total fuel.

**Figure 10 - Combustor Emissions with Simultaneous Inner and Outer Fueling (6 ATM)**

Figure 10 and other test data suggest that there may be a small advantage in terms of reduced NOx emissions through simultaneous inner and outer fueling. At roughly 60 to 75% inner fueling, NOx emissions are slightly reduced from 100% inner fueling although CO emissions rise slightly at a fixed fuel-air ratio. The magnitude of any advantage of combined fueling remains somewhat uncertain being masked by both experimental scatter in the test data and the relatively small potential performance benefit. Test data indicate that at 6 atm and a CO level of 50 ppm, NOx levels on the order of 14 ppm are achieved for values of inner/total fuel of from 75 to 100%.

Observations of the flame at varying inner/total fuel percentages revealed an apparently well-mixed homogeneous flame above an inner/fuel ratio of approximately 65 to 75%. At these ratios the flame is primarily blue with an occasional yellow burst emanating from the injector centerbody. As the inner fuel percentage is decreased below these levels, the flame becomes increasingly yellow and burns off the outer edge of the premixing passage.

If it is assumed that the fuel films on the inner and outer swirler channel walls are uniform, then the optimum inner/total fuel ratio would be directly related to the surface areas of the inner and outer walls. In this situation maximum vaporization would occur with the fuel film evenly divided over the greatest surface area. With the current hardware, the surface area of the inner cylinder is approximately 68% of the outer annulus wall area. Thus an inner/total fuel ratio of 40% should be optimum. However, as indicated by the flow visualization study, the fuel does not film uniformly. Fuel on the centerbody is partly stripped from that surface by the swirling air and thrown to the outer wall. The result is that a higher level of inner fueling produces better prevaporization due to the additional liquid surface area associated with droplet formation.

**Effect of Combustor Pressure Drop: Combined Fueling**

For the fixed geometry combustor evaluated, an increase in combustor pressure drop is brought about by increasing the combustor air flow. Such an action has two major effects. First, to maintain a constant flame...
temperature at the higher air flow rate, a higher fuel flow rate is needed. Consequently, the combustor loading (Btu/hr-ft^3-atm) increases.

The second impact of higher pressure drop and air flow is to increase the air velocity in the swirler premixing channel. As the flow visualization study has documented, a minimum air velocity must be exceeded to produce a uniform fuel film on the injector centerbody.

To explore the role of increased combustor pressure drop on emissions, a series of tests was performed with the combustor pressure drop ratio varied from 3.0 to 5.5%. An excessively high DP/P is undesirable as it adversely affects engine performance. Too low a pressure drop results in poor mixing within the combustor with poor combustion and a non-optimum combustor exit temperature profile being the result.

Tests were run at 6.2 atm with combined inner and outer fueling (75% inner/25% outer) using only air-blast atomization. Emissions data at varying DP/P are plotted in Figure 11. The reduction in NOx emissions resulting from higher DP/P is clearly indicated in the figure. The decrease in NOx is directly attributable to the enhanced premixing and prevaporizing occurring at higher DP/P.

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Effect of Combustor Pressure: Combined Fueling

Effect of Fuel Volatility

A single test was conducted using JP-4 to examine combustor performance on a more easily vaporized fuel than No. 2 diesel. The test was run at 6 atm with air-blast fuel atomization. Fueling was through both the inner and outer filming injectors with a 75% inner/total fuel ratio.

Test results for both JP-4 and No. 2 diesel are shown in Figure 14. On JP-4, 9 ppm NOx could be achieved with CO emissions at 50 ppm. A comparison of the emissions data for the two fuels shows that NOx emissions for the two fuels are very similar. CO
DISCUSSION AND SUMMARY

The JP-4 flames appeared uniform and entirely blue over the range of conditions studied. These observations indicate that a higher level of prevaporization is achieved with the lighter fuel. However, the similarity of the NOx emissions results with the two fuels indicates that the filming injector does an efficient job of fuel vaporization and premixing with the heavier diesel fuel.

Compressor Liner Temperatures

As part of the combustor evaluation, combustor liner temperatures were monitored with a series of 21 thermocouples mounted on the liner outer surface. These thermocouples were oriented in 3 axial rows, the rows being positioned at equal intervals around the liner circumference. Each row contained 7 thermocouples positioned at locations expected to yield high wall temperatures due to flame impingement on the liner inner wall.

The liner temperature data indicated that wall temperatures were maintained below 1600°F, a typical design level for industrial gas turbine combustors, at the highest pressures evaluated.

FIG. 14 - COMPARISON OF COMBUSTOR EMISSIONS ON METHANOL, JP-4, AND NO. 2 DIESEL

Emissions are reduced with the JP-4 at a fixed fuel-air ratio.

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Increasing the combustor pressure drop (by increasing the combustor air flow) acts to reduce NOx emissions although ultimately high CO emissions result due to excessive combustor loading. The impact of the increased air flow associated with increased combustor pressure drop is to increase air velocities within the swirler channel. The increased air velocity has been shown by flow visualization to result in the formation of a more uniform fuel film on the injector centerbody.

Generally, the low emissions combustor ran well when using the filming fuel injectors. Combustion stability and efficiency were good, and liner wall temperatures were low. Within the constraint of maintaining CO levels below 50 ppm, the combustor yielded approximately 12 ppm NOx at 6 atm and 20 ppm at 9 atm. The test data agreed well with typical lean-premixed burner performance showing a rather narrow range of operation in which both CO and NOx concentrations were low.

A potential problem associated with the hardware was the tendency for "coking" to occur at the injector centerbody downstream end during No. 2 diesel operation. No attempt was made to correlate the formation of the deposits with operating conditions or investigate potential effects of the deposits on fuel film behavior or combustor performance. The deposits were observed to increase in thickness with longer test periods but never exceeded several thousandths of an inch. Coking was less severe with increased combustor pressure drop ratio. This suggests that either periodic shedding of the deposits may have occurred with the higher air velocities or that the higher air velocities swept the fuel film off the injector centerbody before coking could occur.

Much less deposition occurred with the lighter JP-4 than with No. 2 diesel. Since the single JP-4 test was conducted immediately following a No. 2 diesel test, the lighter fuel was observed to have acted as a solvent and removed previously deposited material. The coking issue merits further investigation to assess its impact on long term combustor operation.

To emphasize the significance of the reported work, Figure 14 compares the NOx and CO emissions from the current program at 6 atm with comparable data obtained burning methanol, an exceptionally clean burning liquid fuel (Smith, 1983). The methanol test program employed a similar filming injector (inner filming only), air swirler, and can combustor in a test rig evaluation. Test results indicate that somewhat lower NOx levels were achieved with methanol firing although CO levels were higher. If the methanol data were subjected to the 50 ppm CO limit defined for the current effort, the methanol data would show a NOx level only slightly lower than the level achieved with No. 2 diesel. Viewed from this perspective, the initial proof-of-concept testing conducted in this program showed excellent results.

A number of avenues exist for improving the performance of the low emissions combustor/fuel injector from its current state. These potential improvements include:

1. Lengthening the injector centerbody to allow a longer time for fuel vaporization and premixing.
2. Increasing the number of orifices used to deliver fuel to the filming surfaces. A more uniform initial distribution of fuel should aid in the formation of a more uniform fuel film.
3. Modifying the injector centerbody geometry from cylindrical to conical. The result would be an accelerating air flow through the swirler channel.
which should improve filming stability on the centerbody.

- Downsizing the injector (or increasing the combustor volume) to reduce combustor loading. This will act to reduce CO emissions.

- Selectively reducing the volume of air used for combustor liner cooling. Reductions in liner cooling flow through the use of advanced liner cooling techniques act to lower CO emissions.

- Exploring whether a vertical orientation of the fuel injector significantly improves film formation. Gravitational effects that result in a circumferentially non-uniform film distribution on injector centerbody would be avoided.

Although the results of the testing conducted in this program are encouraging, a number of development tasks remain to be completed before the liquid-fueled, lean-premixed gas turbine combustor technology is ready for commercial application.

ACKNOWLEDGMENT

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REFERENCES