VARIABLE GEOMETRY FUEL INJECTOR FOR LOW EMISSIONS GAS TURBINES

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ABSTRACT

To extend the stable operating range of a lean premixed combustion system, variable geometry can be used to adjust the combustor air flow distribution as gas turbine operating conditions vary. This paper describes the design and preliminary testing of a lean premixed fuel injector that provides the variable geometry function. Test results from both rig and engine evaluations using natural gas are presented. The variable geometry injector has proven successful in the short-term testing conducted to date. Longer term field tests are planned to demonstrate durability.

INTRODUCTION

Within the last five years, most industrial gas turbine manufacturers have introduced low emissions machines. This new generation of gas turbines employs lean-premixed (LP) combustion technology as the means to lower NOx emissions. LP combustion provides lower NOx emissions by operating at a reduced, more spatially uniform flame temperature than more traditional diffusion flame combustors.

Although LP combustion can provide lower NOx emissions, it is characterized by a narrow range of fuel/air ratio over which both NOx and CO emissions are low. This is illustrated in Figure 1 which shows the operating range of a typical LP gas turbine combustor without variable geometry (VG) or fuel staging for low emissions range extension. Through the use of VG at part load operating conditions, the flame temperature in the LP combustor primary zone can be controlled to widen the range over which low emissions are achieved.

Two common VG techniques for controlling the primary zone stoichiometry at part load are air bleed from the compressor (effective on one and two-shaft engines) and modulation of the inlet guide vanes (single-shaft engines only). Compressor bleed is effective but results in a larger than normal reduction in turbine efficiency at part load since high pressure air is dumped overboard upstream of the combustor and turbine sections. Modulation of the inlet guide vanes (IGVs) at part load is not associated with a significant efficiency reduction but can lead to excessively high turbine exhaust temperatures in cogeneration applications.

To avoid the disadvantages associated with air bleed and IGV modulation, Solar has been working to develop a VG fuel injector for its SoLoNOx product line. The VG injector directly controls the combustor primary zone air flow without impacting the total air flow through the engine, as do compressor bleed and IGV modulation. As a result there is no part load efficiency reduction attributable to the VG system, and engine exhaust temperatures are identical to those of non-bleed engines.

The VG injector systems will be of particular value for gas turbines in applications where significant time is spent at part load conditions. This will be the case more in applications such as gas transmission than power generation. In addition, VG systems should allow combustor trimming to optimize emissions performance as ambient temperatures vary.

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Fig. 1 - Operating Range of Lean Premixed Fixed Geometry Combustor

NOx (ppm; 15% O2) vs. GAS PRODUCER SPEED, %

Emissions Limits

CO (ppm; 15% O2)

50% Load 80% Load 100% Load
This paper describes the proof-of-concept and prototype testing of a VG injector concept developed for the Centaur 50S gas turbine and subsequently extended to the Mars engine.

OVERVIEW

To develop an improved VG capability, a prototype VG fuel injector for the Centaur gas turbine was designed and a single unit fabricated. Proof-of-concept rig testing of the injector showed that good emissions (NOx <25 ppm; CO <50 ppm at 15% O2) could be achieved over a wide range of simulated engine operating conditions.

Based on the successful single injector tests, a full set of twelve injectors was fabricated. Testing of the injector set was carried out in both high pressure rig and development engine environments. Test results from the evaluations were encouraging with the injectors extending the range of low emissions (NOx <25 ppm and CO <50 ppm) down to the established program goals (50% load for two-shaft engines; 80% load for single-shaft machines).

Following the initial inhouse tests, the VG injector and actuation system designs were modified for improved durability and retested with successful results. A long term field evaluation of the VG system is scheduled to begin by mid-1999 on a Centaur 50 gas turbine in gas transmission service. In addition, the VG injector design has been extended to the Mars gas turbine and development testing is underway.

DESIGN

The development of the VG injector was initially targeted for Solar's Centaur 50S gas turbine. This low emissions engine is capable of meeting NOx and CO limits of 25 ppm and 50 ppm (15% O2), respectively, on natural gas. Table I presents typical full load operating conditions for the Centaur 50. The goal of the development project was to replace the use of compressor air bleed and IGV modulation at part load while still maintaining the low emissions capability and operating range of the LP combustion system.

Table 1 - Nominal Centaur 50s Full Load Combustor Operating Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airflow</td>
<td>38 lb/sec (17.3kg/sec)</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>630°F (606K)</td>
</tr>
<tr>
<td>Inlet Pressure</td>
<td>150 psia (1.02 Mpa)</td>
</tr>
<tr>
<td>Turbine Inlet Temperature</td>
<td>1850°F (1283K)</td>
</tr>
</tbody>
</table>

Figure 2 presents the configuration of the prototype VG fuel injector which uses the production Centaur gas-only injector as a starting point. The production injector design has been described in detail elsewhere (Smith, 1992). The primary design change to the production injector was the addition of an air metering plug at the upstream end of the injector. This conical plug translates axially along the injector centerbody thus varying the inlet area of the primary combustion air swirlers. Figure 3 shows a typical flow characteristic for the Centaur VG injector. The injector was designed so that at the full open position the VG plug had no impact on the effective flow area of the injector.

As illustrated Figure 2, the VG plug is driven by a shaft-mounted cam assembly located within the injector centerbody. The shaft extends through the injector mounting flange and is actuated outside of the combustor casing. During the initial development work, independent electric rotary actuators were used to modulate the injectors. Subsequent actuation system development focused on a unison ring system to drive all twelve injectors as a set (Fig. 4). The unison ring is mounted around the combustor casing and mates with each of the injectors through a rack and pinion combination (Fig. 5). The unison ring rides circumferentially on rollers attached to the combustor casing and is driven by a linear actuator mounted on the casing. The change in actuation system from separate electric actuators for each injector to the unison ring system was made for the purposes of cost reduction and durability enhancement.

TEST FACILITIES

Three test facilities were used during the development of the VG injector.
Single Injector Test Rig

Proof-of-concept testing of the VG injector was conducted in a high pressure combustion rig using a single injector. The rig allows injector testing with an 8 inch (20 cm) diameter, film-cooled, can combustor. Testing can be conducted at high pressure and inlet temperature with scaled air flow. Experience has shown that emissions results from injector testing in this rig are very similar to the results seen in engine tests with full injector sets and annular combustor geometries.

The combustor test rig is depicted in Figure 6. Preheated combustor inlet air enters the rig after metering and flows in a reverse direction around the outside of the combustor liner to the fuel injector. At full load Centaur 50 conditions, approximately 50% of the air flow enters the injector and 50% is employed for liner cooling. No dilution zone is incorporated in the combustor liner.

Further downstream, combustor exhaust gases flow through a water-cooled diagnostic section and a water quench before exiting through a back-pressure valve to the atmosphere.

Instrumentation is available to measure air and fuel flows, gas temperatures and pressures, liner temperatures, and exhaust gas composition (CO, CO₂, O₂, NO, NOx and UHC). Exhaust gas samples are collected using three water-cooled probes at the exit of the diagnostic section.

High Pressure Combustor Test Facility

A second test facility allowed the performance of a full set of twelve injectors to be assessed at part load and near-full load Centaur 50 operating conditions. The facility is structured around a two-shaft Centaur T4000 gas turbine. The test engine has been modified to accept an externally-mounted annular combustor (Fig. 7) rather than the in-line configuration used in the production Centaur.

The test facility delivers an air flow of approximately 36 lb/sec (16.3 kg/sec) at 600°F (589K) or greater, and 110 psig (0.76 Mpa) to the combustor at full load.

The facility is capable of monitoring:

- combustor air and fuel flows
- inlet pressure and temperature
flow rig to establish the calibration between plug position and swirler effective area (Fig. 3).

The injector was installed in the single injector rig and subjected to a series of three tests. For each test the VG plug was fixed in a different location and emissions characteristics measured as a function of overall combustor fuel/air ratio. Inlet temperature and air flow rate were held constant for all tests.

Figure 8 presents the results of these initial tests. NOx and CO emissions are shown for the three different plug settings. The data show the effectiveness of the VG injector in broadening the low emissions operating range of the combustor. Figure 8 shows that moving the VG plug to a new position acted to shift the emissions curves relative to the overall fuel/air ratio. The curve shift occurs as the VG plug alters the flow distribution of the combustor. For a given overall fuel/air ratio, opening the plug acts to lean-out the primary zone, reducing NOx and increasing CO.

**Fig. 7 - High Pressure Combustor Test Facility**
- combustor pressure drop
- combustor liner temperatures
- exhaust gas composition
- combustor pressure oscillations (Kistler probe)
- pattern factor and combustor exit plane radial temperature profile

**Turbine Test Facility**
Ultimately the VG injector set was evaluated in a Centaur 50S gas turbine at Solar. The testing took place in a development test cell maintained expressly for engine and engine component performance evaluations. The test engine was a single-shaft machine employing a production annular combustor liner.

**DEVELOPMENT TESTING**

**Single Injector Tests**
The two goals of the initial VG injector testing were to:
- establish that the addition of the VG plug did not degrade the low emissions capability of the production injector on natural gas
- establish that adequate flow control was available such that air bleed or IGV modulation would not be needed down to 50% engine load for two-shaft machines and down to 80% load for single-shaft turbines.

A single VG injector was fabricated for this proof-of-concept testing. Prior to combustion testing the injector was evaluated in a cold...
The development effort then progressed to an inhouse engine test on a single-shaft Centaur 50S engine. The same hardware used in the high pressure rig facility was installed on the test engine. The same method of setting the VG injectors was used to establish steady state performance. Although this method was not useful for the evaluation of transient behavior, it was judged the most expeditious way to assess the injectors on an engine without having to first develop a production-ready actuation system.

Figure 10 shows typical single-shaft engine emissions data with the VG injectors. As with the earlier rig data (Fig. 9) a simulated operating curve was derived from the data and is presented in Figure 10. The simulated operating curve was used to establish a correlation of VG plug position versus engine load for subsequent inclusion in the engine control system software.

An examination of the engine test data (as well as earlier data) shows that there was increasing difficulty at the lower loads in keeping both NOx and CO below target levels. Figure 10 shows that keeping NOx below 25 ppm at loads below about 70% results in CO above 50 ppm. The likely cause of this behavior is the higher percentage of air flow entering the combustor as cooling air at part load as the VG injector is closed. Any reaction quenching (leading to CO emissions) near the liner walls would be intensified by the relatively higher cooling flow. Also contributing is the lower combustor inlet temperature at part load.

The engine data demonstrate that the VG injector design is successful in extending the low emissions operating range to 80% load without exceeding the NOx and CO emissions limits.

**Actuation System**

Following the injector design verification the project focus shifted to the development of an actuation system that was more suitable for field service. A cost analysis showed that a system based on a unison ring driving all the injectors simultaneously was preferable to electric actuators. In addition the reliability of the unison ring system was deemed superior as the high temperature operating environment around the combustor casing was incompatible with close-coupled electric actuators.

Once fabricated, the unison ring system was assessed by repeating the high pressure rig tests conducted for injector assessment. Figure 11 compares the two-shaft engine test results using the unison ring system and individual actuators. With the unison ring system, engine performance was somewhat degraded from the separate actuator configuration. This was attributed to each injector having slightly different cold flow characteristics. Thus simultaneous actuation of the injectors resulted in a larger effective area spread among the injectors.

![Fig. 9 - High Pressure Rig Performance of VG Injectors](image1)

![Fig. 10 - VG Injector Emissions: Single Shaft Engine Test](image2)

![Fig. 11 - VG Injector Performance With Unison Ring Actuation](image3)
than with individual actuation. Performance was adequate, however, to maintain acceptable emissions down to approximately 70% load.

CONCLUSION

Through this effort a VG fuel injector concept for an LP combustion system was evaluated successfully through rig and engine tests. The VG injector serves to extend the low emissions operating range of the LP combustor to lower engine loads without the use of compressor air bleed or IGV modulation. Thus the loss in engine efficiency associated with compressor bleed can be avoided.

The VG injector hardware proved capable of meeting the program emissions goals (NOx<25 ppm; CO<50 ppm, 15% O2) over engine load ranges of 50-100% for two-shaft engines and 80-100% for single-shaft engines. In addition, a preliminary operating curve of injector area versus load (or gas producer speed) was attained to support the development of injector control algorithms for use by the engine control system.

The injectors operated without any occurrence of high combustor oscillations and with acceptable combustor pressure drops over the operating range investigated.

Additional testing with a unison ring actuation system was successful in demonstrating low emissions but over a reduced operating range. Work is ongoing to increase the sensitivity of the unison ring system and reduce the variation in flow characteristics of the individual injectors. These improvements are expected to provide a level of range extension similar to individual injector actuation. In addition, advanced liner cooling methods that avoid CO quenching are under development for use with the VG injectors. The advanced liners should further extend the low emissions operating range of the VG system.

The final step in the development process will be the long term testing of the system in the field to establish durability. Field testing will also provide the opportunity to optimize the control algorithms that modulate the injectors as engine operating conditions (load, ambient conditions) vary. A field test is scheduled to begin by mid-1999.

REFERENCES