ABSTRACT

This paper summarizes 1/10 scale combustor test results and design parameters that have lead to the fabrication, assembly and test of a full-scale, 22 MW thermal-input (76 mmbtu/hr) combustor and engine system. The engine is a production Allison 501-K industrial turbine that has been modified to accept an external combustor designed for burning coal-water-slurry (CWS) fuel. The combustor utilizes rich-quench-lean (RQL) staging to control emissions of both thermal NOx and NOx formed from nitrogenous compounds contained in the coal-water slurry. Water is injected into the quench zone to freeze molten ash that is formed in the rich zone. The dry ash is removed from the system and collected in storage vessels by passing the hot combustion products through parallel cyclone separators. The cleaned fuel-rich gases pass to the lean zone where the addition of compressor-discharge air results in auto-ignition of the gas mixture and provides sufficient oxygen for completion of the combustion reactions.

Measurements made of emissions from the bench-scale combustor at simulated power conditions show that NOx and CO concentrations of less than 50 ppmv and 15% oxygen can be expected. Check out testing of the full-scale combustor on CWS and the combined combustor/engine assembly on distillate fuel are now in progress. It is anticipated that engine testing on CWS will commence in early 1991.

INTRODUCTION

This work has been performed under a Department of Energy (DoE) Morgantown Energy Technology Center Heat Engines program and is cost-shared by the Allison Gas Turbine Division of General Motors Corporation. The program is aimed at developing the necessary technologies for eventual commercialization of a direct coal-fired gas turbine for industrial applications. The Allison program is targeted at users of co-generation systems in the 3.5 to 5.0 MW electrical output range. A major part of the program has been the development of a direct-fired combustion system that is designed to burn coal fuel with high efficiency, meet all applicable environmental regulations and to remove particulate matter and other compounds from the hot gas path that are harmful to the turbine and to the environment.

The program is now entering the fifth year and has progressed from running bench-scale component development tests to full-scale combustion and engine testing. Most of the major program goals have been achieved and the removal of dry ash from the combustion products has been successfully demonstrated.

An evaluation of the economics associated with the production of coal-water slurries indicates that, due to the relatively few initial users, coal-water slurry will not be a competitive fuel in the near term. A new development effort is now underway that is aimed at modifying the combustion system to burn dry pulverized coal with increased ash levels. This paper describes the development of the coal-water slurry combustion system and the changes that are anticipated in order to burn dry coal.

COAL-WATER-SLURRY FUEL PROPERTIES

Coal-water-slurry fuel property specifications were developed after working with several fuel vendors with the long-term goal of maintaining a large-scale commercial pro-
duction slurry price of less than $3.03/GJ ($3.20/mmbtu). These fuel specifications are shown in Table 1 and were met with fuel supplied by Otisca Industries of Syracuse New York.

Although pilot-scale plant CWS fuel costs were as much as 30 to 50 times this value, projected long-term production costs are expected to be competitive with natural gas prices, providing a sufficiently large market becomes available.

**TABLE 1: CWS FUEL SPECIFICATION**

<table>
<thead>
<tr>
<th>COAL RANK:</th>
<th>HIGH VOL A BITUMINOUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>COAL FEEDSTOCK:</td>
<td>VIRGINIA TAGGART SEAM</td>
</tr>
<tr>
<td>COAL HHV:</td>
<td>&gt; 14800 btu/lb MAF</td>
</tr>
<tr>
<td>COAL SULFUR CONC:</td>
<td>&lt; 1.0 % dry wt %</td>
</tr>
<tr>
<td>COAL ASH CONC:</td>
<td>&lt; 1.0 % dry wt %</td>
</tr>
<tr>
<td>COAL PARTICLE SIZE:</td>
<td>&lt; 5 microns (median)</td>
</tr>
<tr>
<td>SLURRY PARTICLE SIZE:</td>
<td>99 % &lt; 15 microns top</td>
</tr>
<tr>
<td>SLURRY SOLIDS CONC:</td>
<td>&gt; 50% SOLIDS</td>
</tr>
<tr>
<td>SLURRY VISCOSITY:</td>
<td>&lt; 100 cp</td>
</tr>
<tr>
<td>SETTLING CHARAC:</td>
<td>No noticeable settling in 24 hours and slurry being capable of being remixed to original quality with minimal effort following shipment and storage</td>
</tr>
</tbody>
</table>

**COMBUSTOR DESIGN REQUIREMENTS**

In addition to meeting system economic criteria, the key combustor design requirements for this program are:

- To burn coal fuel in a short-residence-time, high-efficiency direct-fired combustion system.
- To control and remove from the hot gas stream gaseous and particulate matter compounds that are considered to be harmful to the turbine and the environment.
- To support this effort, the following areas have been addressed:
  - Coal fuel availability and cost
  - Coal fuel handling and delivery systems
  - Combustor performance with emphasis on carbon conversion, NOx and CO emissions
  - Ash management to ensure that acceptable turbine durability and maintenance intervals are achieved and particulate rates are controlled
  - Sulfur emission control compatible with meeting anticipated environmental regulations and system economics.

To meet these challenging design requirements, a phased combustion program was begun in which a nominal 2.2 MW thermal input (7.6 mmbtu/hr) bench-scale system was assembled and tested to explore the effects of operating parameters on overall combustor performance. After establishing that performance goals could be met, a full-scale, 22 MW thermal input combustor was fabricated and tested on CWS. The full-size combustor has now been integrated with the engine and testing on distillate fuel has been completed. Further testing on coal-water slurry is planned for the near future.

**COMBUSTOR DESCRIPTION**

Figure 1 shows a schematic of the combustion system and the flow splits required for coal-water-slurry fuel. Rich/lean staging was chosen to control both fuel-bound nitrogen and thermal NOx emissions while water quenching is used between the rich and lean stages to freeze the molten slag formed in the rich zone. The frozen or dry ash particles are collected and removed from the hot gas stream, allowing cleaned fuel-rich products to enter the lean zone. Combustion air is added to the fuel-rich gas in the lean zone which results in auto-ignition and complete combustion of the mixture. Dilution air is introduced in a final stage to reduce the gas temperature to that required at the turbine inlet.

Throughout the combustion system castable refractory materials have been used to line the inside walls of the pressure vessels. A two layer construction is used with a hard, slag-resistant refractory material on the inside exposed to the combustion gases. An outer layer of thermally insulating castable refractory is used to minimize the heat transfer from the hot gas to the pressure vessel wall. Typical outer wall temperatures are 477 °K (400 °F) while inner wall temperatures are approximately equal to the gas temperature. Water cooling was avoided where possible in order to minimize heat loss and to maintain a near-adiabatic combustion process.

Gas temperature in the rich zone is
allowed to rise to over 1922 °K (3000 °F) by controlling the fuel/air mixture to a fuel-equivalence ratio of 1.3. Quench zone temperature is limited to 1367 °K (2000 °F), and the lean zone operates at 1700 °K (2600 °F).

Bench-Scale Combustion System

The following is a brief description of the bench-scale combustion system. A more detailed description has been provided in a previous ASME paper (1). The combustor is designed to burn CWs at an equivalent nominal thermal heat input of 2.2 MW and is sized for a nominal airflow rate of 1.3 kgs/sec (2.8 pps). The rich zone is 122 cms (48 ins) long and 15.7 cms (6.2 ins) in internal diameter. Flame stabilization is provided by an axial air swirler and CWs fuel is atomized by an air-assist fuel nozzle. Quench water is sprayed into the rich-zone gases and a horizontal cyclone separator is used to remove particulate matter. Air is injected into a cyclonic lean zone to provide oxygen for complete combustion of the quench zone gases. Dilution air is added at the lean zone exit to reduce the gas temperature to that required by the turbine. An exhaust valve is used to control operating pressure and simulate the engine flow conditions throughout the combustor. Plug-flow residence time for the rich zone is 54 msecs and 70 msecs for the lean zone.

Full Scale Combustion System

The full-scale combustion system is designed to burn CWs with a nominal equivalent thermal heat input of 22 MW and a total airflow rate of 12.6 kgs/sec (27.8 pps). A cross-section of the combustion system is shown on Figure 2. The rich zone nominal residence time in the full-scale design is maintained at 61 msecs by increasing the inner diameter to 44.45 cms (17.5 ins) and the length to 137 cms (54 ins) when compared to the bench-scale system. Multiple fuel nozzles and axial swirlers are used for fuel and air injection. Each of the nozzle and axial swirler assemblies is of the same design as is used in the bench-scale system. In a departure from the bench-scale design, twin vertical cyclones located in parallel are used for particulate removal.

501-K Industrial Engine Modifications

In addition to developing a combustion system, significant effort has been applied to the design and modification of a production Allison 501-K industrial gas turbine engine (designated as a 501-KM engine) to accept an external combustor. The modifications included the removal and replacement of the turbine center casing with a two-piece casting and the fabrication of a hot-gas transition duct. Effusion cooling is used to maintain the duct metal temperatures to less than 1089 °K (1500 °F) at the maximum power condition. Figure 3 shows a cross-section of the engine, the modified center section and turbine inlet ducting. A similar flanged opening on the opposite side of the engine is used to convey compressor-discharge air to the external combustor.

RESULTS

Carbon Conversion Efficiency

Of critical importance is the need to convert all of the fuel carbon in the rich zone to CO and CO2 in order to prevent solid carbon removal from the system in the particle separator, which could result in a subsequent loss in efficiency. During a series of CWs tests on the bench-scale combustion system, rich-zone carbon burn out (CBO) was measured by the ash tracer method (2) by taking particulate samples before and after combustion and determining the sample ash concentrations. Through optimization of the air flow splits between zones, CBO levels in the 98-100 % range were attained. Although CBO varies with
several operating parameters, it was found to be most sensitive to the rich-zone fuel-equivalence ratio (ER). Fuel-equivalence ratio is defined as measured fuel/air ratio divided by stoichiometric fuel/air ratio. Figure 4 shows CBO as a function of rich-zone fuel-equivalence ratio and it can be seen to approach 100% at an ER of 1.3 for the baseline CWS, fuel A.

Two other bituminous CWS fuels, B and C, were run at similar conditions but resulted in reduced CBO levels. A significant difference between fuels is both the median and top particle sizes. The top size of fuel A is 19 microns and that of fuels B and C is greater than 40 microns. Larger coal particles require longer residence times to burn completely and can be a major contributor to loss of efficiency. It is believed that the decreased CBO experienced with fuels B and C is related to the coal particle size distribution.

In addition to bituminous coal-water slurry, a hot-water-dried, subbituminous coal-water slurry (fuel D), produced by the University of North Dakota Energy and Environmental Research Center (UNDEERC) was tested in the bench-scale combustion system. The properties of this CWS are shown in Table 2 together with the bituminous CWS fuels.

Although the coal particle size is similar to fuels B and C, the CBO results show less sensitivity to coal particle size and are also included on Figure 4. These results can be attributed to the increased char reactivity that is typical of the lower rank fuel. The penalties of burning subbituminous fuel are the potential increase in commercial processing costs, lower ash-fusion temperature and increased alkali content. The UNDEERC fuel tested was physically cleaned and acid washed to minimize alkali content but at increased processing cost.

**TABLE 2: CWS FUEL PROPERTIES**

<table>
<thead>
<tr>
<th>FUEL</th>
<th>VENDOR</th>
<th>SEAM</th>
<th>RANK</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>OTISCA</td>
<td>TAGGART</td>
<td>BITUM</td>
</tr>
<tr>
<td>B</td>
<td>OXCE</td>
<td>ELK</td>
<td>BITUM</td>
</tr>
<tr>
<td>C</td>
<td>AMAX</td>
<td>ELK-ADA-CREEK</td>
<td>BITUM</td>
</tr>
<tr>
<td>D</td>
<td>UNDEERC</td>
<td>HORN VILLE</td>
<td>SUBBIT</td>
</tr>
</tbody>
</table>

- **ULTIMATE - % by wt**
  - CARBON: 84.85 83.84 78.73 72.30
  - HYDROGEN: 5.31 5.38 4.39 4.84
  - SULFUR: 0.67 0.66 0.56 0.44
  - OXYGEN: 6.59 2.65 11.25 18.16
  - NITROGEN: 1.73 1.64 3.41 1.45
  - ASH: 0.78 5.38 1.61 2.72

- **MAF HHV KJ/KG**
  - 35054 33666 31492 29703

- **MAF HHV btu/lb**
  - 15106 14508 13571 12800

- **SLURRY CHARACTERISTICS**
  - SOLIDS - wt %: 50.5 50.1 49.7 51.4
  - VISC - cP:
    - 100 1/sec: 30 25 48 270
    - 1000 1/sec: 90 25 76 307

- **COAL PARTICLE SIZE**
  - median: 4.7 14.1 10.0 15.8
  - top: 19 42 41 43

**NOx and CO Emissions**

The rich-zone gas temperature at 1.3 ER is below the 2144 °K (3400 °F) refractory wall temperature limit but results in 70% of the total fuel energy being consumed in the rich zone. Reducing the available fuel energy too much could result in lean-zone combustion inefficiency or flammability problems. By maintaining the lean-zone fuel/air mixture at near stoichiometric, but fuel-lean, most of the carbon monoxide in the inlet gas was fully consumed, leaving only trace concentrations of less than 100 ppmv in the exhaust. The use of hot refractory walls also prevented any CO oxidation reaction chilling that can be caused by the use of cooled metal walls.

**FIGURE 4: CARBON BURNOUT AS A FUNCTION OF RICH ZONE EQUIVALENCE RATIO**

**FIGURE 5: RQL CWS EQUILIBRIUM COMBUSTION TEMPERATURES**
Figure 5 shows the calculated equilibrium gas temperatures as a function of equivalence ratio for a design quench temperature of 1367 °K (2000 °F). At the design point, the calculated lean-zone gas heating value is 872 kJ/scm (23.4 btu/scf) which would normally result in an inflammable mixture. The high inlet gas temperature (1367 °K), and the hydrogen produced in the quench zone through the water-gas reaction are sufficient to result in auto-ignition of the fuel gas once combustion air is introduced. Lean zone fuel gas with a heating value as low as 447 kJ/scm (12 btu/scf) has also been successfully burned under stable combustion conditions (3).

From Figure 5 it may be seen that, in the final stage of combustion, the stoichiometric gas temperature is below 1922 °K (3000 °F). Thermal NOx production is a strong function of gas temperature, and by limiting the maximum it may be temperature at stoichiometric conditions, thermal NOx can be minimized. Control of thermal NOx emissions by means of water injection is a well established and widely used technique that is normally accompanied and limited by an increase in CO emissions. A plot of CO vs NOx emissions illustrates this trend and is shown in Figure 6 for both the bench-scale and full-scale combustion systems. Each data point shown represents a different rich, quench or lean-zone operating condition and is not necessarily the result of data scatter. For the CWS fuel used it may be seen that NOx can be controlled to less than 50 ppmv while the corresponding CO emissions are less than 10 ppmv. The single data point obtained from the full-scale combustor to date

\[ \text{CO ppmv, CORRECTED TO 15% O}_2 \]
\[ \text{NOx ppmv, CORRECTED TO 15% O}_2 \]

**FIGURE 6: RQL COMBUSTOR LEAN ZONE EMISSIONS FROM CWS FUEL**

also apparent. For the fuel tested with 1.7% nitrogen, up to 550 ppmv NOx concentration could be expected with a 50% yield. If it assumed that the thermal NOx contribution is zero, then it may be conservatively estimated that the FBN yield has been reduced to less than 5% by staged combustion.

**Sulfur Emissions Control**

The majority of fuel sulfur is converted to SO2 or SO3 in the lean zone and passes through to the turbine exhaust unless control methods are applied. In-reactor sulfur capture using calcium-based sorbents can be effective under certain fuel-lean and fuel-rich conditions. Capture of sulfur must take place upstream of the separator, however, in order that the sulfur bearing particulate matter can be removed from the system before entry to the turbine. Equilibrium calculations predict that, for a CWS fuel, use of calcium sorbents in the water-quench zone will result in little or no capture for fuel sulfur concentrations of less than 1.5%. With dry coal injection, however, the capture efficiency is enhanced as is shown on Figure 7. Here, the sulfur capture efficiency is calculated from the ratio of sulfur material that is converted to the solid phase in the quench zone to the total sulfur present. The effects of gas temperature on optimum capture efficiency are clearly seen and were determined assuming that the temperature was controlled by the addition of quench water. Experiments run with CWS and calcium hydroxide sorbent have confirmed that little or no capture is possible under fuel-rich conditions. It is believed that the relatively high water-vapor content of the combustion gases forces the capture reaction towards the formation of H2S rather than CaS. This conclusion, which is reached based on equilibrium considerations, is not in disagreement with Abichandani et al (4) who have indicated sulfur capture can be achieved under certain non-equilibrium conditions by rapid quenching
of the sorbent particles at the optimum capture temperature. This process, however, is difficult to achieve and a demonstration of this technique has not yet been performed in a practical combustion system.

**501-KM Engine Testing**

To date, CWS tests have been run on the full-scale combustion system in the rich-quench-lean mode and on the combined engine/combustor assembly on distillate fuel in the lean-quench-lean mode. These tests have demonstrated that the external combustor configuration performs as expected over the power range from idle to maximum power. Further testing of the engine on CWS fuel is expected to be completed by early 1991.

**FIGURE 8: DRY COAL RQL COMBUSTOR SCHEMATIC**

**Use of Dry Coal**

The coal-fired turbine program was initiated in 1986 when several suppliers were preparing barrel quantities of CWS fuel from pilot-scale facilities. Since that time, the anticipated rise in natural gas and distillate fuel prices has not taken place and the potential demand for CWS has diminished. As a result, the fuel process developers have not benefited from revenue generated by increasing sales. The current outlook for a cost-effective CWS fuel in the relatively near term is, therefore, poor. Dry coal, on the other hand, is readily available at a well-established cost. Use of this fuel requires the further development of a reliable pressurized feeding and metering system and minor changes to the combustion system. The development of the component technologies required to burn dry coal has now been initiated and the first full-scale combustor and engine tests are expected to take place towards the end of 1991. The major impact on the combustion system has been a change in the required airflow splits in order to maintain zone temperatures within the combustor design requirements. Figure 8 shows the revised flow splits for a typical bituminous coal with physical properties similar to the CWS shown in Table 1, but with the water removed. Of significance is the reduction in separator mass flow rate by a factor in excess of 50%. Future development of the hot-gas clean-up system will include ceramic barrier filter technology now in development, and these changes will be reflected in a cost savings due to the reduction in required number of filtering elements and pressure vessel size.

**CONCLUSIONS**

A water-quenched RQL combustion system has been successfully developed to run on 100% CWS fuel and to remove ash from the hot gas stream in the dry state. The major conclusions that can be drawn from this work are:

- Operation of rich and lean-zone temperatures in excess of the ash-fusion temperature are made possible through the use of a water-quenching stage followed by ash separation.
- Close to 100% carbon burnout in the rich stage can be obtained by maintaining the rich-zone nominal temperature at 1922 K.
- NOx and CO emissions can be controlled to less than 50 ppmv each through optimization of zone temperatures.
- In-reactor sulfur control through the use of calcium sorbents is limited by the water-vapor concentration in the quench zone. Use of dry coal in place of CWS is expected to enhance capture.
- CWS fuel costs for the immediate future are likely to remain high until a sufficiently large market is established. Dry coal offers the potential for near-term competitive fuel pricing with natural gas, but at the expense of additional capital equipment cost.

Full-scale engine hardware has performed as expected in limited CWS testing when compared with the results from the bench-scale combustion system. Additional work is required in order to fully explore combustor/engine characteristics when operating on CWS fuel.

**FUTURE WORK**

The key technology issues associated with the commercialization of direct coal-fired turbines for co-generation applications are being addressed. Included in this effort is:

- Completion of combustor and engine testing on CWS fuel and demonstration of proof-of-concept with a 501-KM external combustor engine.
- Full-scale barrier filter fabrication and testing based on bench-scale component technology development.
- Testing of a pressurized, dry-coal feed system and engine proof-of-concept demonstration.
ACKNOWLEDGEMENT

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