GAS TURBINE FIRING MEDIUM BTU GAS FROM GASIFICATION PLANT

Piero Zanello  
FiatAvio  
Power Plant Engineering - Power Division

Andrea Tasselli  
FiatAvio  
Combustion Technology

Turin, Italy

ABSTRACT

IGCC (Integrated Gasification Combined Cycle) plants for large scale power generation are becoming more and more attractive.

For a gas turbine generating set to operate on Medium BTU gas, it takes dedicated design of both engine and auxiliaries. A new combustion section, with extensive test support, has been developed. Alternative options to reduce inlet air flow and NOx emissions have been compared and appropriate solutions adopted. All auxiliaries systems have been modified according to the gas fuel characteristics.

Integration between plant systems has been carefully evaluated and a control system implemented in order to reach maximum reliability.

The paper deals with different technical aspects of the engine as well as the plant design.

INTRODUCTION

The integration of a combined cycle in a gasification plant is an evolution imposed for different reasons:

- consolidated gasification technologies available to gasify different low commercial value products or refinery slag.
- increased quantity of those products caused by ambient protection regulations
- government funding to self-production
- high commercial value by-products

The IGCC plants devoted to electric power production initially designed to use coal gas or steel furnace by product gas, now are designed to use gasified refinery residues. Refineries must now balance a reduction of product with an increase of slag.

The integration of a combined cycle gas turbine in such a plant requires a very accurate analysis. The accuracy of the analysis in all the aspects to define the technical-economical proposal has an important effect on the initial investments and on operating results.

Based on such analysis, an IGCC plant is competitive compared to other plants like:

- Conventional plants with desulfuration and denitification
- Plants with partial gasification and conventional combustion

They have increased performance:

- High combined cycle efficiency (approx. 46% referred to electric power in lieu of 34% of a conventional thermal plant, and 90% referred to the total utilized power (both electric and heating power))
- Production costs similar to those of conventional thermal plants with lower emission values
- Evolution of potential technologies in order to increase efficiency (target 52%) and reduce emissions levels.

Shortcomings are:

- Higher investments costs
- More interconnected systems
- Insufficient knowledge to guarantee performance of large power plants.
- Insufficient operational data to evaluate operation and maintenance costs.

The present project concerns an IGCC plant to be installed in a refinery plant to convert heavy oil feedstock to syngas with production of co-products like hydrogen and nitrogen.

The gasification process

The gasification families, according to the process criteria, are:

- fixed bed type
- fluid bed type
- entrained bed type

In order to utilise syngases on gas turbines, the selection criteria are based on the following requirements:

- total residue conversion
- process pressure over 20 bar
- simplified plant
- proved technologies

The present project utilises a Texaco entrained bed type gasification plant.

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This system is able to gasify liquid as well solid products, operate at high temperature (1500°C), with short residence time, utilising mainly oxygen and some steam. The resultant syngas contains hydrogen and carbon monooxide. The ashes are vitrified (iron silicate, aluminium, calcium magnesium, titanium) and can be utilized as inert. This type of gasifier is able to treat also bituminous coals, petroleum coke, refinery residues, or emulsions. That emulsion of bitumen extracted in Venezuela (Orinoco basin), a low cost fuel, seems the ideal fuel to demonstrate the total competitiveness of IGCC plants.

The system is constituted of four principal blocks:
- A Feedstock Gasification Unit (FGU).
- An Air Separation Unit (ASU) producing oxygen for the gasification process.
- A Process Plant Unit (PPU) to clean the raw gas.
- A Combined Cycle Unit (CCU) composed by gas turbine, steam turbine, steam generator (HRSG).

Two process are present in the FGU:
- oxidation with production of CO₂, H₂O, SO₂
- reduction with production of CO, H₂, CH₄, H₂S
(see Fig.1)

The primary oxidizer is the oxygen fed by the ASU (exothermic reaction), the secondary is the oxygen contained in the steam (endothermic reaction).

The ASU separates the oxygen and the nitrogen with a cryogenic process. The air could be fed by the gas turbine compressor or by a separate compressor.

The gas purified through the PPU could be mixed with nitrogen or saturated with steam to reduce NOx emissions. Approximate 20% of raw gas could be fed to an Hydrogen Extraction Unit to obtain pure hydrogen.

Refinery residues
The refinery plant treats approximately 13 million of tons/year of petrol.

Residues available to the gasification process to produce a medium BTU gas total 240 tons/hour. The average composition is:
- Carbon 85.7% weight
- Hydrogen 9.15
- Sulphur 5
- Nitrogen 0.6
- Sodium 150 ppm
- Nickel+Vanadium 800 ppm
- LHV 9200 kcal/kg
- Density 1.1 kg/liter
- Viscosity at 100°C 190 cts

Syngas characteristics
Syngas n°1 = Wet Syngas fed by the Gasification Unit with simultaneous production of 40000 Nm³/h of H₂
Syngas n°2= Wet Syngas fed by the Gasification Unit without H₂ production. (see Table 1)

Gas turbine
The machine is a result of 45-year history of developing and manufacturing large heavy duty combustion turbines for industrial and utility service. It is the current production version of the large 50-Hz combustion turbine first developed by Westinghouse and its licenses, Fiat Avio and Mitsubishi, in the mid-1970s. This development was derived from the highly successful Westinghouse model W501 series of large 60 Hz units, first introduced in the later 1960s. The combined Westinghouse/Fiat/Mitsubishi fleet of such large combustion turbines totals more than 300 operating units. Collectively they display an excellent record of high reliability, availability and economy both in simple and combined cycle applications.

<table>
<thead>
<tr>
<th>Composition (% vol.)</th>
<th>Syngas n°1</th>
<th>Syngas n°2</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>24.97</td>
<td>29.05</td>
</tr>
<tr>
<td>CO</td>
<td>34.50</td>
<td>30.52</td>
</tr>
<tr>
<td>CO₂</td>
<td>4.12</td>
<td>4.19</td>
</tr>
<tr>
<td>N₂</td>
<td>0.38</td>
<td>0.34</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.27</td>
<td>0.23</td>
</tr>
<tr>
<td>O₂</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Ar</td>
<td>0.76</td>
<td>0.67</td>
</tr>
<tr>
<td>H₂S + COS</td>
<td>150 ppm max</td>
<td>150 ppm max</td>
</tr>
<tr>
<td>HCN + NH₃</td>
<td>40 ppm max</td>
<td>40 ppm max</td>
</tr>
<tr>
<td>Ni + Fe carbonyls</td>
<td>2 ppm max</td>
<td>2 ppm max</td>
</tr>
<tr>
<td>Total dry gas</td>
<td>65.00</td>
<td>65.00</td>
</tr>
<tr>
<td>H₂O</td>
<td>35.00</td>
<td>35.00</td>
</tr>
<tr>
<td>Total wet gas</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>LHV kcal/kg</td>
<td>2029</td>
<td>2123</td>
</tr>
</tbody>
</table>

The Westinghouse family experience burning medium to medium BTU gas is an additional important success factor for the project. Plaquemine (Dow Chemical) and Kawasaki Steel projects, based respectively on W501D5 and TG50D5 machines, are the most important and direct experiences providing background and operating data as a starting point for the proposed engine and system configuration. A 8 years-long experience has been accumulated by Plaquemine Power Plant, burning a 239 BTU/SCF gas from coal gasification process (41.41% H₂, 38.52% CO, 0.11% CH₄, 18.49% CO₂ and 1.48% Ar+N₂).

Extremely good results have been achieved in terms of plant availability and reliability as well as of emission control. Similar good results have been experienced by Kawasaki Steel Power Plant. The plant has been operative since 1987 and has accumulated more than 50,000 operating hours, burning a 112 BTU/SCF gas, composed by blast furnace gas mixed with coke oven gas, which are byproducts in steel works.

In addition to extensive data base from lab tests as well as the mentioned field experience already available within the Westinghouse/Fiat Avio/Mitsubishi H1 technology family, in order to provide data on the actual project gas composition a devoted lab test program has been launched.

The program includes tests on cannular combustor designed for syngas both at low and high pressure, utilizing fuel having the gas composition indicated in Table 1. The tests were devoted to verify the adopted design solution, collect data for design optimisation and provide information for the combustion and engine control, in this way reducing field optimisation activities.
IMPACT ON THE PLANT
Air compressor flow
To operate with medium BTU gas the GT compressed air is fed to the combustion section must be reduced of approximately 6%.

The percentage of steam has been limited to 35% vol.; in injection process

The impact on the plant imposed by utilizing one or the other of the solutions is rather different:
To have the same NOx reduction, nitrogen quantity to be mixed is larger than steam (approximately 3 times as much). That requires larger size piping. Due to the gasification plant type, the saturation process requires a simpler system than nitrogen injection process

The steam saturation method has been preferred for that reason. The percentage of steam has been limited to 35% vol.; in consequence only a 150 mg/Nm3 NOx emission level has been reached. A catalyst, sized to reach the required NOx value, was installed on the exhaust section.

Final syngas separator and syngas control skid
The final separator and the gas control system has been designed according the new gas fuel conditions. The standard gas system had been designed to utilise natural gas or other gas with a LHV higher than 4450 kCal/Nm3 (500 BTU/SCF).

The use of a medium BTU gas, as that utilised in this project, requires larger sized pipes, valves, injectors, considering that the gas flow will be approximately five times the corresponding natural gas flow.

The gas pressure at the gasification unit outlet is defined by the gasification process conditions. In order to reduce the piping losses, and avoid a gas compressor unit (higher investment costs and reduced efficiency of the entire plant) piping sections have been even increased.

According to that target the design has defined:
- 18" Piping instead of 8"
- Regulation valves in parallel to avoid extremely large size valves.
- Pipe heating to avoid condensate (high steam content).
- Oversized gas system skid.

Enclosures
Gas turbine enclosure and auxiliaries systems enclosure have been oversized to contain the syngas systems and piping.

Safety
The particular syngas composition (high hydrogen and Carbon oxide content) imposes classification areas, where gas piping is installed, in Class 1 Division 2 Group B according NFPA 70.

The affected areas are:
- Gas turbine enclosure
- Auxiliary systems enclosure
- Gas detection and treatment area

The gas detection and treatment area is in the open air and the standard configuration was adequate.

All components installed on the gas turbine enclosure and auxiliaries enclosure are explosion proofing type. In the standard configuration only gas skid components are explosion proof.

Also fuel oil skid, lubeoil skid, water injection skid are equipped with explosion proof components.

The standard gas turbine and auxiliary enclosures ventilation systems were both provided with three 50% capacity extraction fans, two in operation and one in stand-by. For this application the system will be provided with two 100% capacity fans, one in operation and one in stand-by.

Purge time will be increased in order to assure that the total volume is exchanged six times in lieu of three as per standard.

The gas piping vent system has been implemented with a nitrogen purge system to assure, at fuel changeover or at trip, the total elimination of syngas. A system with bottles, piping, valves and automation was added.

The gas detection system already existing on standard gas turbine and auxiliary enclosures, was been improved with CO detectors, to assure personnel safety.

Supervision and control system
The gas turbine control system will be integrated into the IGCC control and supervision system as far as the Refinery supervision system. For this purpose the GT control system must be able to talk to all equipment and main control systems.

An accurate analysis has been done to achieve:
- definition of type and number of information inputs and outputs
- definition of interface devices
- verification of transmission times

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IMPACT ON THE ENGINE

Combustion Section: Introduction

From the combustion point of view, a medium to medium BTU content fuel gas, such as the syngas derived from the gasification of heavy oils, doesn’t pose unsolvable problems. In the past several diffusion flame technology combustors capable of working with syngases with an LHV of 900 kCal/kg and below were demonstrated to work more or less flawlessly with a variety of G/T engines. Design goals for this combustor were set to attain, with the lowest emission levels possible, the maximum durability of the combustor hot parts. Also of primary design concern was to maintain the maximum operating flexibility by ensuring stable syngas combustion throughout the operating range of the engine including load rejection and crank-up.

Combustion Section: Design Considerations

As said above, the design of a combustor for a syngas application is quite a straightforward matter, since the choices given to the combustor engineer are basically the same ones for conventional (i.e. diffusion flame natural gas/oil feed) combustors but with some additional caveats.

One is that one has to take into account the higher flame speed of syngas (that is, for a syngas with significant amount of H2). As depicted in Fig.2 (where a comparison is made of the atmospheric laminar flame speed of H2 and CH4 as a function of the equivalence ratio, ) the hydrogen flame speed is several times greater than that of methan, or of any other hydrocarbon. This means that a fuel gas containing an appreciable amount of hydrogen (as is this case, see Table 1), will have a rather short flame compared to that of methane-based natural gas. It turns out that having a shorter flame impacts on the cooling requirements of the combustor dome and on the primary zone local equivalence ratio.

Another problem facing the combustion engineer is that the amount of fuel injected through the combustor fuel ports is much greater than the typical amount of natural gas (the amount actually depends on the LHV of the syngas). The designer is therefore forced to adopt a different design approach then the ones based on natural gas when designing these gas ports. This may require changing some standard design practice to fit the new conditions. Also having such a large amount of gas feed calls for a careful dimensioning of primary, secondary (if any) and dilution scoops (chutes) together with sizing cooling air devices devoted to keep the combustor wall temperature down. Depending upon the designer’s approach to the primary zone equivalence ratio (suppose a lean primary zone is wanted) one might be forced to inject a large amount of air through the primary scoops which may be at odds with cooling or dilution air requirements.

These and others constraints (transition duct cooling requirements, pattern factor, turbine inlet profile, oil firing requirements, emission limitations) surface throughout the design and sometimes impose design choices which might not be enough proven or are totally new. This usually leads to hot rig tests of the combustor prior of installing it onto the engine to expose design flaws or to check the combustor performance against the expected one. A better approach (at least with new designs) is to include the combustion tests within the design cycle and to use the test rig(s) as just another design tool available to the combustion engineer.

The combustor was designed around two operating conditions considered critical to the design; Base Load and No Load conditions. Table 2 and 3 give the combustor parameters for each of engine conditions for the gas listed in Table as Syngas N°1:

All conditions refer to 15 °C external temperature and 70% humidity. Syngas inlet temperature was set at 493 K. As for the nomenclature used T3 stands for combustor air inlet temperature, P3 stands for combustor shell pressure, P4 is turbine inlet pressure, Wp is the fuel flow and Wp-Wf is the combustor air flow (obviously Wf is the turbine inlet flow).

<table>
<thead>
<tr>
<th>T3</th>
<th>P3</th>
<th>TTT</th>
<th>P4</th>
<th>Wp</th>
<th>Wp-Wf</th>
</tr>
</thead>
<tbody>
<tr>
<td>[K]</td>
<td>[kPa]</td>
<td>[K]</td>
<td>[kPa]</td>
<td>[kg/s]</td>
<td>[kg/s]</td>
</tr>
<tr>
<td>668.33</td>
<td>1510.37</td>
<td>1523.33</td>
<td>1438.46</td>
<td>54.33</td>
<td>347.79</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>T3</th>
<th>P3</th>
<th>TTT</th>
<th>P4</th>
<th>Wp</th>
<th>Wp-Wf</th>
</tr>
</thead>
<tbody>
<tr>
<td>[K]</td>
<td>[kPa]</td>
<td>[K]</td>
<td>[kPa]</td>
<td>[kg/s]</td>
<td>[kg/s]</td>
</tr>
<tr>
<td>601.67</td>
<td>948.72</td>
<td>892.22</td>
<td>903.91</td>
<td>12.66</td>
<td>303.68</td>
</tr>
</tbody>
</table>

As the first step of the design phase it was decided that the equivalence ratio for the primary zone had to fall on the lean side, with the equivalence ratio of 1.0 as the higher bound and 0.7 as the lower one. During the design phase engine operability constraints showed that to gain enough stability margins (set at 20%) at No Load cond’s the equivalence ratio in the primary zone had to be 0.83.

After various attempts with some standard (plain hole) fuel nozzle configurations it was decided that the best gas nozzle configuration to match an oil fuel injector was a gas swirler injector (as shown on Fig.3). The pressure drop was set at 2 bar and the swirler area and number and angle of blades set accordingly. Also into the design of the fuel swirler went considerations on flow recirculation/mixing (that is, Swirl Number) in the primary zone which led us to adopt an curved blade configuration with 45° exit angle and a 32 blades swirler. The mixing/recirculation capability of the primary zone was improved further by designing two air swirler injectors around the gas swirler. To simplify manufacturing the air swirler blades were set to be straight. To enable double firing, as required by the application, a simplex-type oil injector was fitted, with a 250 gph capacity and a spray angle of 50°. Water injection when running on oil to curb emissions is attained by injecting water through the atomizing air holes.
To provide for enough combustion air and a good mixing/recirculation flow pattern within the primary zone a six primary scoops configuration was chosen. It showed a good compromise between manufacturing complexity, flow stability and jet penetration, the last one being the paramount design concern. To save on air and because of the very short syngas flame it was decided to eliminate secondary scoops. Cooling requirements, especially in the primary zone, and lack of air required the adoption of special cooling devices for the basket walls. They were chosen to be the MHI's PlateFin cooling rings (see Fig.4). They give a better ratio of kg/s of air to surface cooled to a given temperature than conventional (film cooling, impingement cooling) devices.

To provide for dilution air a three scoops configuration was chosen, with the same scoop diameter of the primary ones, to save on manufacturing costs. The basket was also fitted with an exit cone to reduce CO. Basket layout and main features are shown in Fig.5.

Combustion Section: Combustor Testing

As most of the design choices made through the design phase were based on standard practices with no support from CFD codes or complex chemical codes and, given the novelty of such a design within FiatAvio, it was decided to have an extensive run of rig tests to confirm the suitability of such a design to the requirements. Also the steep requirements in terms of both CO and NOx emissions required some confirmation prior to the installation of the combustors into the engine. To go as near as possible to real thing the tests were carried out with the same syngas composition that was to be used with the engine, i.e. Syngas N°1. The tests were performed at the AIT (Aero & Industrial Technology Ltd) test facility of Burnley, Manchester, UK. The test rig was built up to FiatAvio spec.'s and it is shown in Fig.6. The rig inner geometry was made so to simulate as closely as possible the TG30D5 pressure shell inner layout.

Two batch of tests were planned and another one was later added to further investigate the behavior of the syngas combustor. Prior of these tests a complete flow check of the combustor's effective areas was made. The first of the batch was carried out at low pressure (near atmospheric) to investigate the ignition, stability and lean extinction limits of the syngas combustors. The test article was fitted with instrumentation such as static pressure taps, metal temperature T/Cs and pressure fluctuation probes as well as with an UV detector and a spark plug for ignition. The basket instrumentation layout is shown in Fig.7. The test rig was fitted with static pressure and temperature taps and also with two gas sampling/temperature, a water-cooled moving rake with 5 sample probes for gas analysis and with 5 temperature probes at the T/D exit (see Fig.8) and a fixed position, single water-cooled probe (gas analysis plus temperature) further at the so-called EPA plane (this probe conforms to EPA requirements).

Low Pressure Tests:

The tested conditions were scaled with the flow function from 6 different engine conditions, that is from No Load (0%) to Base Load (100%) in 20% power increments. The simulated conditions as recorded on the rig are shown on Table 4.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>601</td>
<td>129</td>
<td>874</td>
<td>0.101</td>
<td>567</td>
<td>2.42</td>
</tr>
<tr>
<td>611</td>
<td>129</td>
<td>1006</td>
<td>0.149</td>
<td>411</td>
<td>2.22</td>
</tr>
<tr>
<td>621</td>
<td>129</td>
<td>1105</td>
<td>0.184</td>
<td>386</td>
<td>2.04</td>
</tr>
<tr>
<td>633</td>
<td>129</td>
<td>1234</td>
<td>0.217</td>
<td>407</td>
<td>1.81</td>
</tr>
<tr>
<td>653</td>
<td>129</td>
<td>1317</td>
<td>0.239</td>
<td>399</td>
<td>1.74</td>
</tr>
<tr>
<td>669</td>
<td>129</td>
<td>1394</td>
<td>0.26</td>
<td>400</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Ignition was attained at a rather low F/A with respect to nominal conditions, to prevent the possible accumulation of large quantities of unlit fuel at the stack prior of ignition.

Weak extinction limits were investigated at each of the above conditions by reducing fuel flow in small steps (~ 10%) until the exhaust thermocouples indicated flame extinction. Also a rich point (nominal + 20%) was run to investigate flame stability in the rich zone (flame extinction tests at rich conditions were not run because of the risk of having a large amount of syngas fuel at the exit stack). Results for ignition, weak extinction and rich running are shown in Fig.9.

Emissions (NOx, CO and UHC) were recorded at the T/D exit and at the EPA plane and are shown in Fig.10 and 11 (no correction is made for O2). Combustion efficiency was in excess of 99.7%. Maximum metal temperature topped at 1123 K in the first cooling ring when running the 100% load simulated condition. Visual investigation after these test showed some distortion on the dome cooling skirt indicating temperatures around and over 1173 K, possibly caused by the very short flame occurring at low pressure conditions.

Overall these tests showed that the combustor was performing with good ignition characteristics and with a wide stability range. Also emissions, especially CO emissions were much lower than expected and were a good omen for the remainder of the tests.

High Pressure Tests:

Since the AIT rig has a limitation of the maximum working pressure at 9 bar, full pressure tests could not be performed. Instead scaled down pressure test to match available rig pressure were performed. Testing conditions simulated engine running at No Load and Base Load conditions.

Actual rig conditions are given in Table 5. To investigate combustion behavior when running with diesel #2 oil with water
injection, simulated Base Load tests were run with different water/fuel ratios. Oil test conditions are given in Table 6.

### Table 5 - Syngas High Pressure Simulated Test Cond’s

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>602</td>
<td>526</td>
<td>897</td>
<td>0.409</td>
<td>445</td>
<td>9.86</td>
<td>100%</td>
</tr>
<tr>
<td>666</td>
<td>740</td>
<td>1528</td>
<td>1.47</td>
<td>488</td>
<td>9.4</td>
<td></td>
</tr>
</tbody>
</table>

During the No Load test at high pressure the ignition was carried out with no problems. This was not possible at the Base Load cond’s because the amount of fuel needed to rise up the rig pressure to that condition was not enough if the test was to be run to its full duration. It was decided therefore to raise the rig pressure by oil running and performing a fuel switch over to syngas once reached the test cond’s. The fuel transfer was carried out in 20% increments from syngas to oil. The fuel transfer was successful with no signs of combustion instabilities during the process. During Base Load the with syngas a complete exhaust traverse reading at sixteen equally spaced angular positions at T/D exit. After this test a simulation of engine load rejection was attempted by suddenly cutting down the fuel flow (but not that of air, to simulate the much slower reaction time of engine’s IGV closing) to the No Load fuel flow. During this process there were no problems with flame stability and stable combustion was achieved at the reduced fuel flow.

Syngas emissions test results (all the NO\textsubscript{x} emission values are dry - 15% O\textsubscript{2} corrected, all the other emission are on dry basis) are given in Table 7. Combustion efficiency was found to be in excess of 99.9%.

Figure 12 gives the traverse temperature profile (in °C) for syngas running. As typical with most syngas combustors the exit profile is quite flat. Pattern Factor was computed to be 0.07.

The highest recorded metal temperature was about 1150 K in the second cooling ring, this showing that the flame peak has moved downstream from the position it took when running at low pressure, as it was expected because of the higher fuel flow. The FlateFin cooling rings, especially those of the primary zone performed quite well under the increased thermal load getting away with only a 30 K increase in maximum metal temperature. Combustion-induced pressure fluctuations when running the syngas high pressure tests were rather small if not negligible.

**Table 7 - High Pressure Syngas Emissions**

<table>
<thead>
<tr>
<th>Engine Cond.</th>
<th>Sample Position</th>
<th>NO\textsubscript{x} [ppmvd]</th>
<th>CO [ppmvd]</th>
<th>UHC [ppmvd]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>Traverse Mean</td>
<td>3.0</td>
<td>26.6</td>
<td>0.0</td>
</tr>
<tr>
<td>0%</td>
<td>EPA Plane</td>
<td>3.0</td>
<td>24</td>
<td>0.0</td>
</tr>
<tr>
<td>100%</td>
<td>Traverse Mean</td>
<td>20.4</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>100%</td>
<td>EPA Plane</td>
<td>22.9</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

On oil running a complete exhaust traverse reading was carried out at each of the test conditions (i.e. with different water/fuel ratios). Emissions results are given in Table 8.

**Table 8 - High Pressure Oil Emissions (w/ water injection)**

<table>
<thead>
<tr>
<th>W/F</th>
<th>Sample Position</th>
<th>NO\textsubscript{x} [ppmvd]</th>
<th>CO [ppmvd]</th>
<th>UHC [ppmvd]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>EPA Plane</td>
<td>59</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>0.78</td>
<td>EPA Plane</td>
<td>45</td>
<td>0</td>
<td>1.4</td>
</tr>
<tr>
<td>0.96</td>
<td>EPA Plane</td>
<td>35.6</td>
<td>0</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Basket metal temperature were found to be lower than with syngas with a peak maximum temperature of ~ 893 K. This was expected because of steam injection and because of a longer more narrow flame shape. Pressure fluctuations were rather high (up to +/- 2% of inlet air pressure) but with a frequency of about 10 Hz (with a cut-off analyzer value of 10 Hz) which led to suspect a rig pressure shift (linked to compressor’s own frequency) superimposed to some combustor’s natural mode.

**Additional Low Pressure Tests:**

These tests, although not planned for at the beginning of the test program, were carried out to investigate the syngas combustion properties while changing steam content (25%, 36% to 45%, the case with 35% steam added being already tested). There was just enough syngas left in the tanks to carry out a complete batch of tests at only low pressure conditions. The tests consisted of an ignition test (for each syngas composition) at No Load simulated condition, where the fuel was increased from the nominal equivalent No Load condition up to stable ignition (the flame would stay lit when reducing fuel flow). The rig conditions at which stable ignition occurred are listed in Table 9. To assess influence of inlet air temperature the 25% steam syngas case was run at atmospheric air temperature.

**Table 9 - Ignition Tests Results**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>2.57</td>
<td>309</td>
<td>125</td>
<td>424</td>
<td>0.0249</td>
</tr>
</tbody>
</table>
After these tests a full performance campaign was carried out trying to investigate the properties of these syngas compositions at Base Load simulated conditions. Table 10 gives the relevant conditions.

<table>
<thead>
<tr>
<th>Steam Content</th>
<th>Air Flow</th>
<th>Air Temp.</th>
<th>Air Pressure</th>
<th>Fuel Temp.</th>
<th>FAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>1.65</td>
<td>576</td>
<td>130.3</td>
<td>384</td>
<td>0.136</td>
</tr>
<tr>
<td>36%</td>
<td>1.66</td>
<td>666</td>
<td>130.6</td>
<td>428</td>
<td>0.169</td>
</tr>
<tr>
<td>37%</td>
<td>1.66</td>
<td>667</td>
<td>130.5</td>
<td>438</td>
<td>0.161</td>
</tr>
<tr>
<td>38%</td>
<td>1.66</td>
<td>667</td>
<td>130.2</td>
<td>441</td>
<td>0.165</td>
</tr>
<tr>
<td>39%</td>
<td>1.68</td>
<td>667</td>
<td>130.6</td>
<td>439</td>
<td>0.165</td>
</tr>
<tr>
<td>40%</td>
<td>1.67</td>
<td>674</td>
<td>129.3</td>
<td>445</td>
<td>0.167</td>
</tr>
<tr>
<td>41%</td>
<td>1.66</td>
<td>664</td>
<td>130.7</td>
<td>446</td>
<td>0.171</td>
</tr>
<tr>
<td>42%</td>
<td>1.66</td>
<td>669</td>
<td>131.2</td>
<td>469</td>
<td>0.174</td>
</tr>
<tr>
<td>43%</td>
<td>1.66</td>
<td>668</td>
<td>129.5</td>
<td>483</td>
<td>0.178</td>
</tr>
<tr>
<td>45%</td>
<td>1.66</td>
<td>668</td>
<td>132.5</td>
<td>500</td>
<td>0.183</td>
</tr>
</tbody>
</table>

The emission values (all emission values are not corrected either for dry basis or 15% O₂) are listed in Table 11 and 12. Due to the limited amount of syngas available some of the gas analysis was carried out by using the fixed EPA probe instead of the traverse probe. Combustion efficiency, as before, was in excess of 99.99%.

The emission results for both Syngas No.1 and Diesel fuel #2 Base Load tests, that is, the NO₄ level, were transposed to the actual engine conditions to give the following (all values are dry - 15% O₂).

As expected, NO₄ emission went down as the steam content of the syngas increased (in a rather linear manner). Fig. 13 and 14 give the trend of CO and NO₄ emissions vs syngas steam content.

In the end these tests showed that the syngas combustor gave good performance when handling different syngases. CO emissions, source of primary concern, did not increase when increasing the syngas steam content and seemed to reach a plateau of minimum value at nearly the maximum steam content. Stability at all conditions was satisfactory (pressure fluctuations well below 10 kPa).

Transposition of Results to engine conditions

The emission results for both Syngas No.1 and Diesel fuel #2 Base Load tests, that is, the NO₄ level, were transposed to the actual engine conditions to give the following (all values are dry - 15% O₂).
• Syngas N°1 → from 20.4 to 32.4
• Oil w/ W/F=0.6 → from 59 to 85
• Oil w/ W/F=0.78 - from 45 to 65
• Oil w/ W/F=0.96 → from 35.6 to 50

To give these corrections the usual formula correcting NO\(_x\) emissions (i.e. (NO\(_x\) (full pressure) / NO\(_x\) (partial pressure))\(^n\)) for pressure differences was used. With the Syngas N°1 a 0.65 exponent was used while the usual 0.5 exponent was used for the Oil case.

FINAL CONCLUSIONS

As the tests showed, the syngas combustor design proved quite robust and performed well especially with respect to the required emission levels. Although minor modification to the hardware are required in order to improve durability (by lowering metal temperature in the primary zone), we think that the basic design is sound and leaves enough room for improvements.

REFERENCES


Geoffroy, Amos, 1991, "Four Years Operating Experience Update on a Coal Gasification Combined Cycle Plant with Two100 Mw Gas Turbines": Combined Heat and Power and Independent Power Producers Conference 18th - 20th June, 1991


Fig. 1: Functional Block Diagram of the Plant

Fig. 2: Laminar flame speeds of $H_2$ and $CH_4$ at 1 atm and 25 °C
Fig. 3: Injectors Section for Syngas Combustor

Fig. 4: PlateFin Cooling Ring
Fig. 5: Syngas Combustor Layout

Fig. 6: Rig Layout
Fig. 7: Instrumentation Layout

Fig. 8: Traverse Sampling Probe
Fig. 9: Low Pressure Syngas Stability Margins (dashed area)

Fig. 10: NOx emissions

Fig. 11: CO emissions
Base Load Exit Temperature Profile [°C]

![Exit Temperature Profile (Syngas)](image)

Fig. 12: Exit Temperature Profile (Syngas)

**CO emissions vs Steam Content (%)**

![CO emissions vs Steam](image)

Fig. 13: CO emissions vs Steam

**NOx emissions vs Steam Content (%)**

![NOx emissions vs Steam](image)

Fig. 14: NOx emissions vs Steam