

**ADVANCED GAS TURBINE COMBUSTION SYSTEM DEVELOPMENT
FOR HIGH HYDROGEN FUELS**

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ABSTRACT

Integrated Gasification Combined Cycle (IGCC) technology makes possible the utilization of low cost coal and opportunity fuels, such as petroleum coke, residual oil and biomass, for clean efficient and cost effective electricity generation. Siemens is a leading supplier of products and services for IGCC plants and it is adapting its most advanced gas turbines for successful integration into IGCC plants. To expedite this, Siemens is pursuing combustion system development for application in IGCC plants operating on syngas/hydrogen fuels.

Detailed combustion system testing has been carried out during 2005 and 2006 on syngas/hydrogen fuels derived from different feed stocks and gasification processes. The test programs addressed both the F- and G-Class firing temperatures and operating conditions. Fuel transfer capability to and from natural gas, which is the startup and backup fuel, and syngas was explored over the operating range. Optimization studies were carried out with different diluent (H₂O and N₂) addition rates to determine the effect on emissions and operability. The focus of this development was to ensure that only combustion system modifications would be required for successful enriched hydrogen syngas fuel operation. This paper summarizes the results from the Siemens combustion system development programs to demonstrate that low emissions and wide engine operating range can be achieved on hydrogen fuel operation in advanced 50 Hz and 60 Hz gas turbines in IGCC applications with carbon dioxide capture.

INTRODUCTION

Recent increases in natural gas prices and concerns about its availability, as well as significant advances in air separation, gasification and syngas cleanup

technologies, have made coal and opportunity fuels based Integrated Gasification Combined Cycle (IGCC) plants a competitive option for efficient and environmentally safe power generation compared to direct fired pulverized coal plants and natural gas fired combined cycle (CC) plants. The main incentives for IGCC technology development and application are the low fuel costs, significant reduction in emissions and high efficiency in future plants. The current IGCC plant capital costs with CO₂ capture are higher than for conventional coal based plants. However, the availability and abundance of coal, petroleum coke and residual oil, help to make IGCC's cost of electricity and total plant life cycle costs more competitive. The development of a syngas/hydrogen capable combustion system is the key prerequisite for the successful gas turbine (GT) integration into an IGCC plant with CO₂ capture.

It has demonstrated excellent performance, reliability, availability and exceptional flexibility, as well as low emissions in the Siemens 50/60 Hz heavy duty gas turbines [1-6]:

- SGT6-5000F, 60 Hz, 200 MW class, 192 Units, 3500 thousand operating hours (kOH) [1-3]
- SGT6-6000G, 60 Hz, 270 MW class, 22 units, 250kOH [4-6]
- SGT5-4000F, 50 Hz, 300 MW class, 105 units, 2173 kOH
- SGT6-4000F, 60 Hz, 185 MW class, 41 units, 586 kOH

All four advanced gas turbine models have the required attributes for successful integration into future IGCC plants. To enable this integration, extensive combustion development programs have been carried out or are in progress to develop reliable, low emissions combustion systems capable of operation on a broad

range of coal and opportunity fuels derived syngas/hydrogen fuel. Beside these Siemens funded development programs, several major research programs are funded by government to develop combustion systems for syngas/hydrogen operation in advanced IGCC concepts, including those with CO₂ capture:

- High Efficiency Gas Turbine for Syngas Application (HEGSA) Project, funded by the European Commission
- Enhanced CO₂ Capture Program (ENCAP), funded by European Union
- “Rich Combustion Lean Burn” catalytic combustion system [7] for Natural Gas (NG) and syngas operation in the SGT6-5000F engine, funded by United States Department of Energy (DOE)
- Phases 1 and 2 of the Advanced Hydrogen Turbine Development Program [8], funded by DOE

Siemens heavy duty GTs have accumulated more than 320,000 hours of successful operating experience on syngas in IGCC plants located in Europe and the United States and on low heat content gases, such as blast-furnace gas [9-13]. Additionally, many small industrial size GTs, ranging from 7 to 25 MW, have operated on syngas and high hydrogen content refinery gas fuels for more than 750,000 hours. Table 1 summarizes Siemens’ experience on syngas and high

hydrogen content fuels. This paper focuses on the development of hydrogen fuel combustion system for Siemens advanced F/G class gas turbines.

COMBUSTION SYSTEM TEST RESULTS

The objectives of the combustion system development test were to demonstrate that NO_x emissions would be restricted to 15 ppm (at 15% O₂) on syngas/hydrogen and 25 ppm on NG and that CO emission would be kept below 10 ppm for all fuels. The test program was also to verify the combustion system operability over the load range, fuel transfers between natural gas/syngas/hydrogen, and co-firing with different fuels.

The combustion system development testing was carried out in the Single Burner Full Pressure Combustion Test Rig, which was modified for syngas operation (see Figure 1). The facility has capability for superheated steam generation, which is required for syngas and natural gas dilution purposes. Additional fuel constituents, such as H₂, CO, CH₄, CO₂ and N₂, are supplied the test site. The syngas or hydrogen fuel is simulated by mixing these constituents. For hydrogen test, the hydrogen was premixed with nitrogen and/or superheated steam.

The combustor tested was a diffusion flame combustor. Figure 2 shows the prototype combustor basket and fuel nozzle.

Gas Turbine	Plant Location	Main Features	Fuel	Startup
SGT-200	Many Locations		80-85% H ₂	
SGT-500/600	Many Locations		20-90% H ₂	
VM5	Dortmund, Germany	Compressor Drive GT	Blast-Furnace Gas	1960
VM5	Handan, China	Compressor Drive GT	Blast-Furnace Gas	2000
CW201	Chicago, USA		Blast-Furnace Gas	1960
V93	Luenen Germany	First CC plant in the world with integrated LURGI coal gasification	Syngas	1972
2XSGT6-3000E	Plaquemine, USA	CC plant with integrated DOW coal gasification	Syngas	1987
4XSGT6-3000E	Sweeney Cogeneration L.P., USA	CC Plant	0 – 30% H ₂	1998
SGT5-2000E	Buggenum, Netherlands	CC plant integrated with coal gasification (hard coal and biomass blend)	Syngas	1994/5
V94.3	Puertollano, Spain	CC plant integrated PRENFLO coal gasification (coal and petroleum coke blend)	Syngas	1997/98
2XGT5-2000E	Priolo Gargallo, Italy	CC plant with integrated GE heavy-oil (asphalt) gasification	Syngas	1998/99
SGT5-2000E	Servola, Italy	CC plant with steel-making recovery gas	Steel-Making Recovery Gas	2000
SGT5-2000E	Sannazzaro, Italy	CC plant with integrated SHELL heavy-oil gasification	Syngas	2005

Table 1. Operating Experience with Syngas and Hydrogen Fuels

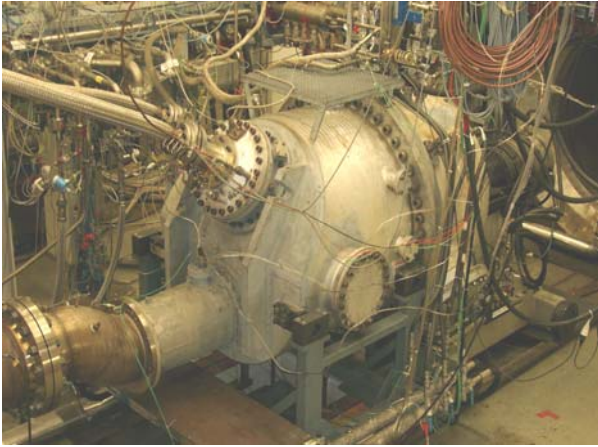


Figure 1. High Pressure Combustion Test Rig



Figure 2. Syngas/Hydrogen Capable Prototype Combustor

SGT6-5000F Combustion System

After the 2005 rig test program [14], production combustor hardware was designed and used in the latest rig test. In addition to the verification of the production hardware syngas operation performance, the main focus was the hydrogen rich gas testing. Pure hydrogen with nitrogen and/or steam and high hydrogen gas after 90% CO₂ capture were tested. The syngas/hydrogen fuels tested are given in Table 2 (after dilution).

mol%	Syngas		H2	
	min	max	min	max
H2	11%	22%	30%	73%
CO	21%	34%	0%	46%
CH4	0%	4%	0%	5%
CO2	1%	11%	0%	14%
N2	5%	41%	0%	60%

Table 2. Diluted Syngas/Hydrogen Gas Compositions

The test measurements, which were recorded in real time, included emissions, combustor dynamics, gas temperature and combustor metal temperatures. Tests were first carried out at the F-Class firing temperature on different syngas compositions and natural gas. They confirmed the results on syngas and natural gas operation obtained in 2005 [14]. Subsequently, hydrogen rich gases were tested with only nitrogen and steam as diluent. Also, high hydrogen gas (about 77% hydrogen) to simulate 90% CO₂ capture was tested with different dilution levels. Similar to the previous syngas results [14], the recent test showed that the diluent type (steam or nitrogen) and hydrogen fuel heating value had a strong impact on NO_x emissions. NO_x emissions increased from low single digits with increasing fuel heating value (see Figure 3). For the same NO_x emission, diluent requirement was minimized when using steam. Figure 4 correlates the relative NO_x emissions to the stoichiometric flame temperature with the same set of data shown in Figure 3. The relative NO_x is defined by normalizing the NO_x emissions to a NO_x value at a reference stoichiometric flame temperature. Figure 5 shows the NO_x emissions variation with load on a particular diluted pure hydrogen fuel. The NO_x emissions were well within the target value.

In conclusion, the combustion system tests were completed successfully and all the emissions and operational targets were demonstrated (see Table 3). Stable combustion was achieved on both the syngas, hydrogen, and NG fuels, as well as fuel transfer between syngas/hydrogen/natural gas. Co-firing with different fuel combinations between 30% and 90% loads was demonstrated in the rig test. Combustion dynamics and combustor metal temperatures were well within design limits for all tests. The test results demonstrated that the selected combustor/fuel nozzle combination will meet its design goals for syngas/hydrogen operation in an IGCC application.

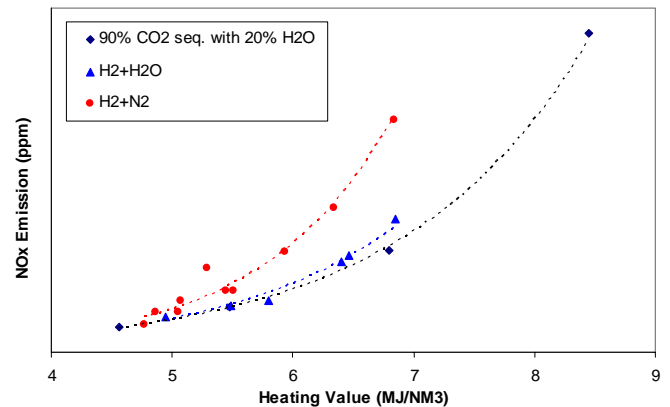


Figure 3. Effect of Hydrogen Heating Value on NO_x Emissions

SGT6-6000G Combustion System

The SGT6-6000G combustion system is almost identical to that in the SGT6-5000F combustor test. The operational differences are the higher firing temperature (Turbine Inlet Temperature), air flow and pressure in the SGT6-6000G combustor. Any combustion system advancements developed on the SGT6-5000F are directly transferable to the larger engine model. The test results on syngas and hydrogen rich fuels under G firing temperature were very encouraging. Figure 6 compares the syngas/hydrogen test results under SGT6-5000G firing temperature and the hydrogen data under SGT6-5000F firing temperature as shown earlier in Figure 4. The stoichiometric flame temperatures were adjusted by changing dilution level.

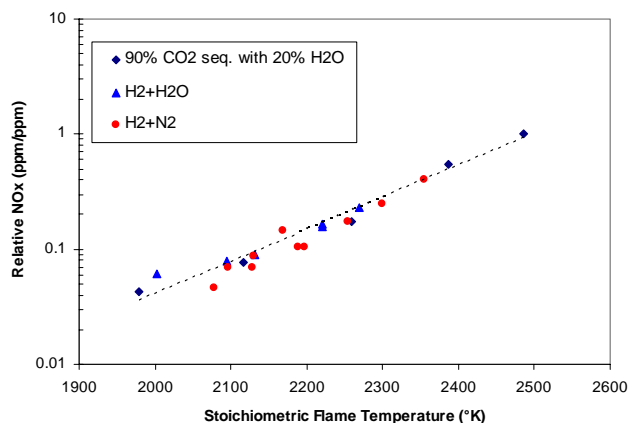


Figure 4. Correlation of Relative NOx with Stoichiometric Flame Temperature

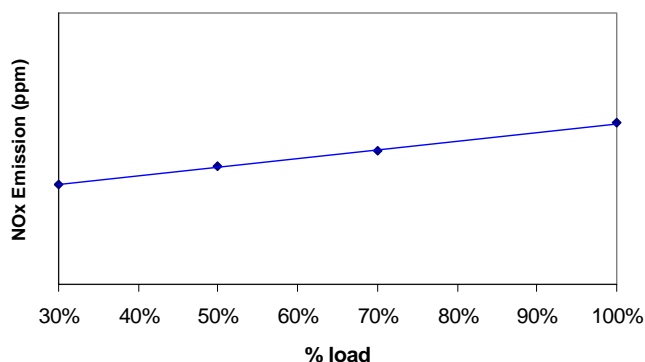


Figure 5. NOx Emission vs. Load for H₂+N₂+H₂O Mixture

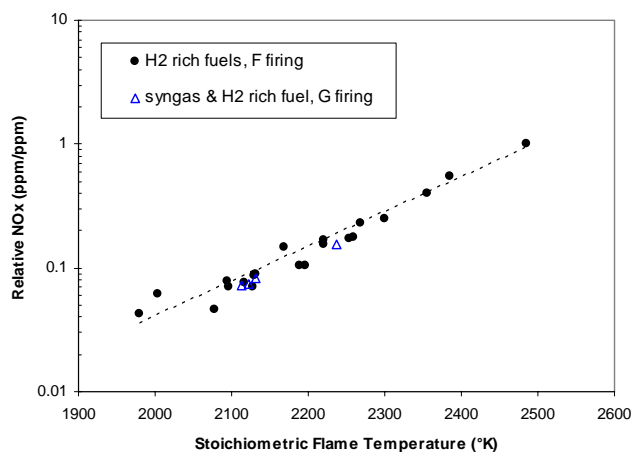


Figure 6. Comparison of Test Results under SGT6-5000F and SGT6-5000G Conditions

SGT5-4000F Combustion Tests

The premixed syngas combustor design developed for SGT5-4000F in HEGSA [14] was used in the ENCAP project to test hydrogen rich fuel gases. Figure 7 shows this prototype burner design.

Combustion tests were conducted with pure hydrogen with various diluents and dilution levels (H₂: 40-55%, N₂: 9-50%, H₂O: 9-50%, LHV: 4.4-5.8 MJ/NM³) at full pressure engine conditions to demonstrate flashback resistance with the highly reactive fuels. Figure 8 shows the mapping of the flashback margin with hydrogen rich fuel (inverse Damkohler number vs. Wobbe number). The Damkohler number was defined as the ratio of the chemical reaction time scale to the flow mixing time scale. This plot shows the two mechanisms of flashback in this burner design: reactivity and mixing field. With hydrogen content increasing, the reactivity of the gas mixture increases and results in flashback at certain conditions. As with the Wobbe number drops with dilution, the stronger fuel jet disturbs the fuel/air mixing flow field and results in flashback at certain conditions.

Fuel		Emissions, ppm	
		Expected Engine Results	Test Rig Results
Syngas	NOx	15	<15
	CO	10	<10
Pure H ₂	NOx	15	<15
	CO	0	0
Natural Gas	NOx	25	<25
	CO	10	<10

Table 3. SGT6-5000F Combustion Test Target and Results Summary

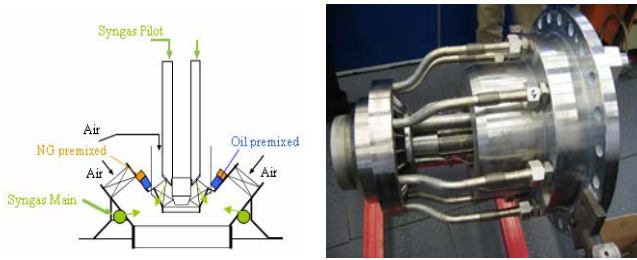


Figure 7. SGT5-4000F Triple-Fuel Syngas Combustor

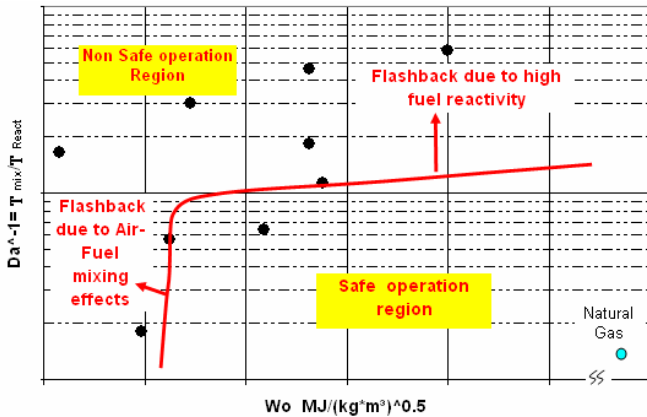


Figure 8. Mapping of Flashback Margin of Hydrogen Rich Fuel

MODIFICATIONS FOR IGCC APPLICATION

SGT6-5000F Modifications

The SGT6-5000F engine is being offered commercially for IGCC applications as the SGT6-PAC 5000F [15]. To expedite its successful integration into IGCC plants, a reference plant design was produced. To verify that the SGT6-5000F can be used in this application, detailed analyses were carried out on all the affected components. The existing and redesigned components were analyzed for the worst case scenario for each individual component to ensure that all design criteria and limits would be satisfied. Aerodynamic, heat transfer, thermo-mechanical, and life cycle analyses were carried out on the compressor, turbine, rotor and casings. The combustion system components were designed to operate on syngas and NG. The cover plate was modified for syngas operation and the fuel nozzle was designed to accommodate multi-fuel operation, diluent injection, fuel transfers and co-firing.

Syngas/hydrogen operation has a significant impact not only on the combustor and the hot end components, but also on the compressor, since its surge margin changes due to the increased operating pressure ratio resulting from the increased syngas fuel mass flow. A detailed investigation was carried out on the compressor

surge margin to determine if the first stage turbine vane had to be restaggered open to reduce the operating pressure ratio. Two vane open staggers and no restagger cases were investigated. The detailed compressor analysis results showed conclusively that adequate surge margin would be maintained without requiring the vane restagger.

Turbine analysis concluded that all its components would meet the design requirements when operating on syngas and would not require any modifications. Combustion cylinder analysis demonstrated that it was acceptable at the higher operating pressure. It did not require any modifications for air extraction, since the air required for the gasification process will be withdrawn through the two existing manway openings located on opposite sides of the combustion cylinder. No engine exterior physical interfaces were impacted with the exception of those on the combustor cover plate which was redesigned to accommodate syngas operation. All modifications for syngas operation are completely retrofitable into existing engines. This will allow current SGT6-5000F operators the option for future conversion to IGCC operation.

In addition to the engine modifications, the other systems of the SGT6-PAC 5000F were also evaluated. Modifications to supervisory instrumentation, auxiliaries and controls will be required for syngas/hydrogen operation.

SGT6-6000G Modifications

Conceptual modifications are being developed for the SGT6-6000G gas turbine operation on coal derived hydrogen and syngas fuels in IGCC plants. Performance, emissions and RAM will be evaluated and optimized. Cost impacts associated with the proposed component modifications and with the overall system are being evaluated. This is being investigated to ensure that the SGCC6-6000G IGCC plant concept will be economically viable. Detailed designs will then be carried out for the new components and any required component modifications.

RECENT DEVELOPMENTS

Siemens has been developing a catalytic combustion system for the SGT6-5000F gas turbine over the past four years using the Rich Combustion Lean Burn design concept. Most of this effort has been focused on natural gas fuel, but recent development under the "Catalytic Combustor Development for Fuel-Flexible Turbine Program", co-funded by U.S. DOE, is making good progress in developing the catalytic system for operation on syngas and high hydrogen content fuels. Selected catalyst materials were identified, down selected and validated on NG, syngas and hydrogen. The necessary catalytic module design changes were incorporated. Test results showed that emissions goals were achieved

on NG. The performance of the catalytic module design on syngas/hydrogen operation is being evaluated.

U.S. DOE awarded Siemens a cooperative agreement for Phases 1 and 2 of a 10-year program to develop the SGT6-6000G gas turbine for integration into an advanced, highly efficient, near zero emissions, coal-based IGCC plant. Various combustor concepts will be evaluated for hydrogen/syngas fuel burning capability with minimum emissions. Some of these concepts include: catalytic, premixed dry low NO_x, and diffusion combustors. They will be tested, evaluated and down selected to one successful candidate, which will then be further developed for incorporation into future SGT6-6000G gas turbines.

The combustion system developments, described above, for syngas operation in IGCC applications will be coordinated so that any enhancements or new concepts developed in one program will be incorporated across the Siemens gas turbine product line, as deemed applicable. By leveraging these R&D efforts, enhanced syngas capable combustion systems will be developed, such that they are fuel flexible, reliable, cost effective and produce minimum emissions.

FUTURE EMISSIONS CONSTRAINTS

IGCC is one of the most promising technologies for reducing emissions from coal-based electricity generation. With proper equipment and maintenance, IGCC plants can meet all current and future expected emissions regulations. Current U.S. emissions regulations on NO_x, SO_x, CO, Unburned Hydrocarbons (UHC), Volatile Organic Compounds (VOC), particulates, mercury, etc., vary from state to state. In general, emissions limits range (at 15% O₂) as follows: (1) On NG: NO_x 3 to 15 ppm, CO < 10 ppm, UHC < 10 ppm, VOC < 10 ppm, and (2) On Distillate Oil: NO_x 15 to 25 ppm, SO₂ 5 to 10 ppm, CO < 20 ppm, UHC < 20 ppm, VOC < 20 ppm, PM₁₀ < .07 kg/MW_{hr}. In Europe the air emissions limits are not as restrictive. For instance, emissions limits on NO_x are 15 to 25 ppm. Based on past experience, emissions regulations are likely to be tightened in the future. In the U.S. CO₂ emissions restrictions, emissions trading and "buyouts" by plants which exceed their permitted emissions limits are on the horizon. These future emissions regulations and restrictions will impact IGCC technology applications/commercialization and GT/combustion system developments for IGCC applications. In the U.S., NO_x emissions regulations will tend to < 5 ppm or even < 3 ppm, depending on the particular state or region. The other harmful emissions limits will also be reduced. The new regulations are working their way through Congress and EPA, but it will take some time before anything is finalized. In Europe, the NO_x emissions limits are likely to remain at < 15 ppm for the near future.

SUMMARY

Detailed combustion system testing has been carried out on hydrogen rich syngas fuels to demonstrate low emissions capability. Fuel transfers between syngas, hydrogen and natural gas, as well as co-firing between 30% and 90% load, were demonstrated in the test. Combustion dynamics and combustor metal temperatures were within design limits for all tests. The test results proved that the combustor design for IGCC application can be readily used to meet the low emissions requirement and wide engine operating range on high hydrogen content syngas fuel operation in advanced 50 Hz and 60 Hz gas turbines in IGCC applications.

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