

Introduction to the Complementary Fired Combined Cycle Power Plant

POWER-GEN International 2006 – Orlando, FL
November 28-30, 2006

Power Generation

SIEMENS

Introduction to the Complementary Fired Combined Cycle Power Plant

Authors

John H. Copen (Presenter of Record)
Siemens Power Generation
4400 N. Alafaya Trail, MC: Q2-286
Orlando, FL 32826
407.736.5403 (T)
407.736.5032 (F)
john.copen@siemens.com

Terrence B. Sullivan
Siemens Power Generation
4400 N. Alafaya Trail, MC: Q2-286
Orlando, FL 32826
407.736.2575 (T)
407.736.5032 (F)
terry.sullivan@siemens.com

ABSTRACT

This paper challenges the conventional method of fuel-based bottoming cycle power augmentation in a combined cycle plant, in which a fuel source is combusted in the hot flue gas stream internal to a combined cycle HRSG - also known as supplementary firing or duct firing. Although duct firing is an effective means of increasing plant capacity, it significantly reduces the plant efficiency. Additionally, as the world fuel markets continue to incur a substantial increase in demand, power plant owners and operators are more actively seeking plant solutions that provide better performance flexibility.

To provide a solution that would allow plant owners better dispatch options, a system was developed that provides base load outputs with maximum efficiencies as well as incrementally selectable peaking outputs with high plant efficiencies. Termed as Complementary Fired Combined Cycle (CFCC), this system is predicated on the use of fractionally sized gas turbines, with their exhaust ducted into the HRSG(s) associated with their base GT(s). This configuration offers very high peak loading efficiency as well as the possibility to increase the level of power augmentation due to its unique impact on the HRSG. This system can be applied to new unit construction, and also has the potential to be retrofitted into plants with and without existing duct firing systems.

This paper explains the Complementary Fired Combined Cycle plant design concept and compares its plant performance characteristics with conventional duct fired plants. Retrofitting applications are also explored. Ancillary advantages of the CFCC plant are enumerated, along with economic comparisons of plant Life Cycle Costs.

INTRODUCTION

Traditional methods for combined cycle peak loading, although effective for providing power, are not well suited to the current global energy and economic models in which higher peak plant efficiency is steadily becoming a critical design criteria. For this reason, a novel concept for providing enhanced combined cycle performance, both on a power and on a heat rate basis, was developed. This document describes this system and provides specific performance calculations for the application of currently available equipment.

This system can be applied to new unit construction or as a retrofit to already existing power plants as a power peaking application or a heat rate reduction option. This art departs from the traditional concept of combusting a supplemental fuel directly in the path of the flue gas in the HRSG(s), as detailed in U.S. Patent # 6,606,848, "High power density combined cycle power plant system" and instead uses high efficiency industrial-sized gas turbines and generator sets (shaft power being converted to electrical energy through electrical generators and being delivered to grid) as a combusting venue while using the same HRSG(s) of the base combined cycle power plant to recover the rejected heat of the industrial GT(s).

This concept fits particularly well when considered and used for high ambient temperature peaking applications since the typical HRSG design basis is a cold day application when the largest flue gas mass flows are achieved. As ambient temperatures increase, the base GT exhaust mass flow(s) decrease, thereby allowing ample flue gas mass flow augmentation capacity.

DESIGN CONCEPT

The general concept of this system is the introduction of additional energy to the flue gas path of a GT / HRSG set by introduction of the waste heat of an industrial sized gas turbine. In this system, referred to as Complementary Firing, additional fuel to augment the bottoming cycle output is first combusted in the complementary industrial sized gas turbine. The exhaust of the complementary turbine is then mixed into the base GT flue gas path in the HRSG. This differs from the conventional peak loading scheme, in which fuel is combusted directly in the HRSG.

Configuration

The conceptual design basis for the Complementary Firing system (Figure 1) entails a power plant consisting of:

- At least one base gas turbine (topping or Brayton cycle) with at least one HRSG and at least one steam turbine, (bottoming or Rankine cycle).
- At least one industrial or complementary gas turbine and generator set, also called the complementary topping cycle or complementary Brayton cycle.

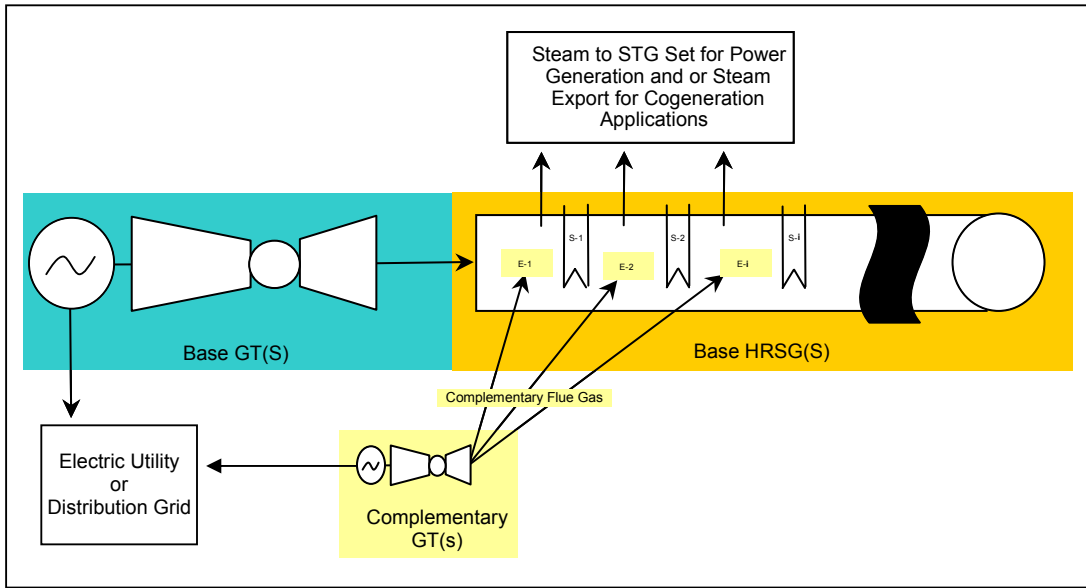


Figure 1. Design Concept for Complementary Firing System

The multiple Interface Points shown in the above Figure represent the possible tie-in points that merited evaluation.

Interface Points

In order to optimize the plant performance in complementary fired mode, several possible HRSG interface points where the complementary topping cycle exhaust gas mixed with the base exhaust gas were studied. As can be seen in Figure 1, three possible insertion points were considered. They are:

1. Position 1 – downstream of Main GT Exit and upstream of HRSG Inlet
2. Position 2 – downstream of Re-Heater #3 and upstream of Re-Heater #2
3. Position 3 - downstream HP Super Heater #1 and upstream of Re-Heater #1

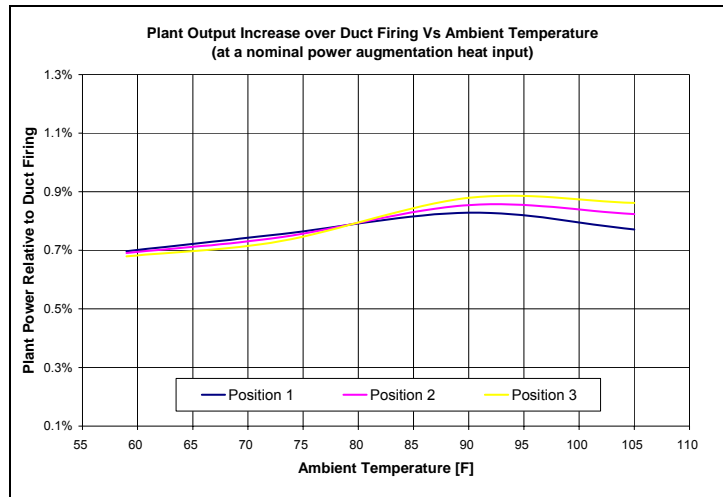


Figure 2. Performance Comparison of Different Interface Positions

It can be seen that the performance attributes achievable with complementary firing do not vary greatly with changing interface points, differing no more than 0.1% from one another in this calculation. This means that there is some flexibility regarding the tie-in point. Given that the 'Position 3' interface point offers a slight performance advantage in this analysis, ensuing calculations will be based on this configuration.

Hybrid

Another possible application of the complementary topping cycle is to integrate it into an existing combined cycle plant that is already equipped with duct firing. The conceptual basis for this hybrid design is identical to that shown in Figure 1; it is in the simultaneous operation of the two distinct power augmentation systems where it varies markedly from the non-duct fired configuration.

PERFORMANCE

By using the power augmentation fuel in the topping cycle in addition to the bottoming cycle, the Complementary Firing System can contribute significantly to higher MW sales as well as fuel savings

Improved Thermal Performance

The performance benefits of fuel utilization in combined (Brayton & Rankine) cycle operation versus Rankine cycle operation are well known. Figure 3 demonstrates the impact of both duct firing and complementary firing on plant performance.

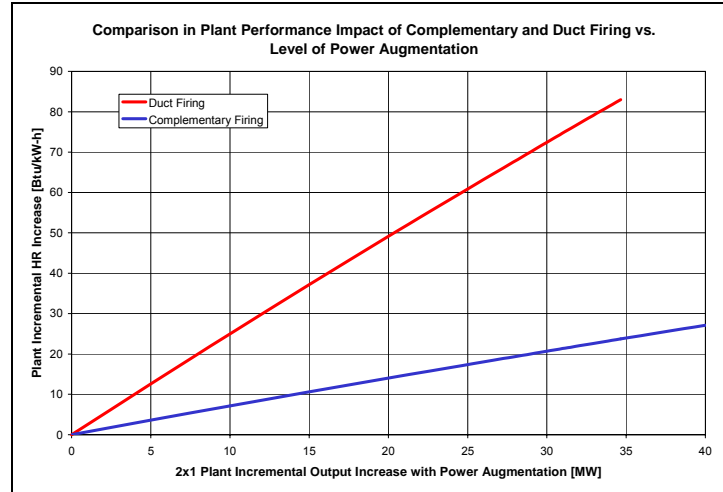


Figure 3. Plant Performance Comparison for Duct and Complementary Firing

It can be seen from Figure 3 that the Complementary Firing System carries a much lower heat rate burden than does its supplementary firing counterpart. Calculations done to date yield a Complementary Firing incremental plant heat rate of ≈ 6500 Btu/kWhr (LHV), which is $\approx 7\%$ higher than the nominal combined cycle heat rate. This compares favorably with the supplementary firing incremental heat rate of ≈ 7500 Btu/kWhr, which is 23% higher than the nominal combined cycle heat rate.

The calculations from Figure 3 were performed based on the assumption of constant heat input to the power augmentation system. Because of its superior fuel utilization

rate, the Complementary Firing System produced 15% more additional output than would duct firing.

Incremental Capacity

The Complementary Fired System plant design matches the flexibility of conventional duct firing in terms of selecting the level of design and operating plant power augmentation.

In the design phase, the project-specific plant power augmentation targets are used to select the class and number of complementary topping cycles required. Given the range of gas turbine outputs available (<20MW to >50MW) and the fact that it is possible to install multiple supplemental systems on each base HRSG, design flexibility is high.

When operating the plant in complementary fired mode, the output can be adjusted by part loading the complementary topping cycle(s) as needed. Figure 4 demonstrates a power augmentation scheme whereby increases up to 65MW are possible through changes to the engine loads and number in service. Other combinations of gas turbine products and multiplicity can be used to meet project-specific demands.

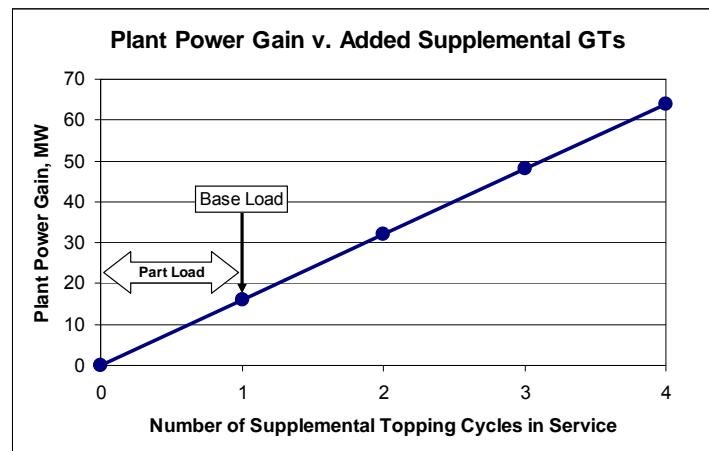


Figure 4. Example of Incremental Power Augmentation Operating Profile

Hybrid System

The Complementary Fired System is an attractive option for increasing the capacity of existing power plants, even those with existing duct firing systems. A hybrid fired system was studied to determine whether the addition exhaust gas from complementary topping cycles into a duct fired HRSG would yield performance improvements. The results of this calculation are shown in Figure 5.

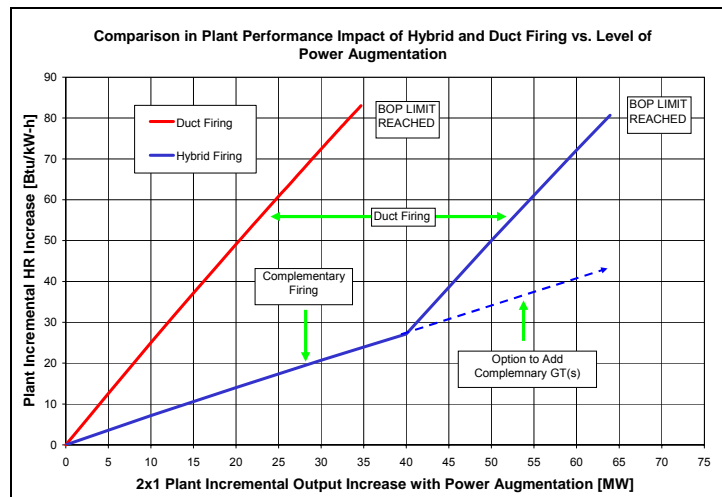


Figure 5. Hybrid System Performance in Plant with Duct Firing

By first using the Complementary Fired System, it is possible to increase plant output to or above levels achievable by the plant's existing duct firing system. This is due to the fact that the CFS does not tax the bottoming cycle as heavily as straight duct firing, thus it does not drive the bottoming cycle to equipment limits as quickly. Additional plant output can then be obtained by firing both the CFS and the duct firing systems simultaneously. The exhaust flow added by the CFS can also help deliver needed Oxygen to the duct firing system (depending on relative location of the two systems), and assist in maintaining the exhaust temperature downstream of the duct firing system below the maximum limit.

FURTHER PLANT BENEFITS

In addition to the plant power and efficiency benefits achievable with the Complementary Firing System, there are some other tangible advantages to having this added equipment. They include:

- **Black Start Capacity:** Given the flexibility and relative ease with which the industrial GT within the Complementary Firing system can be started and loaded, thereby producing sufficient electrical output to power the balance of the requisite plant-wide start-up equipment, the industrial GT could be used as the plant's "Black Start Generator(s)", thereby replacing the current art of using stand-alone diesel and or gasoline powered generators.
- **Auxiliary Steam Capability:** If it is feasible to operate the industrial GT of the Complementary Firing system in a power islanding mode to provide auxiliary power to the overall plant when the plant is in standby or non dispatched modes, it is possible that the waste heat of the Complementary GT can be recovered and converted to a viable source of auxiliary steam.
- **Fast Starting Capability:** As needed, it may be possible to develop a system by which a Complementary Firing system is used in conjunction with existing portions of the base HRSG(s) and or a separate smaller HRSG(s) and or other heat exchanger(s) to produce the necessary conditions, such as seal steam and or thermal pre-heating / warming capacity, that will enable a more rapid

start sequence of the entire combined cycle plant, also known as “Fast-Starting Capability.”

- **Reduced Bottoming Cycle Duty:** When using the Complementary Fired System, approximately 2/3 of the power augmentation originates in the gas turbine, with only 1/3 coming from the bottoming cycle. It thus follows that in comparison to duct firing, in which all of the increased output is generated in the bottoming cycle, the Complementary Fired System does not require as severe a duty on bottoming cycle equipment such as HRSG tubing, pumps, valves, piping, and steam turbine equipment. It stands to reason that maintenance costs for this equipment may be ameliorated.
- **Equipment Size Reductions:** Duct firing imposes strenuous operating conditions on bottoming cycle equipment, and often represents the extreme of the operating envelope around which plant equipment is sized. One example of this is the Air Cooled Condenser (ACC), which is typically sized to provide a suitable steam turbine back pressure on a hot day with maximum duct firing. By transferring duty from the bottoming cycle (duct firing) to the Complementary Firing gas turbines, the steam turbine mass flow is reduced and the ACC duty is lowered. This allows for a reduction in the size and cost of the ACC, or improvement to the hot day steam turbine performance, or both.
- **Cold Day Peaking:** It is not uncommon for the cold day duct fired power augmentation to be significantly curtailed due to bottoming cycle equipment limitations. Since the Complementary Fired System transfers less energy to the bottoming cycle for every MW of power generated, it may be possible to make more incremental power before hitting equipment limitations.

ECONOMICS

In order to provide an economic comparison of a plant fitted with complementary firing and a conventional (supplementary fired) plant, the performance and cost impacts were collected. The metric of ‘Net Present Value’ was used for this activity.

Performance

The performance of the two systems was compared based on a constant heat input to power augmentation equipment, and was evaluated across the higher temperature range in which power augmentation is normally employed. The higher efficiency of the complementary cycle lead to increased plant power output and decreased plant heat rate as compared to supplementary firing:

Ambient Temperature	Power Compared to Complementary Firing [MW]	Heat Rate Compared to Complementary Firing [Btu/kW-h]
59 F	4.3	-41
90 F	4.6	-51
AVERAGE	4.4	-46

The performance delta is converted into economic terms through the use of economic evaluation criteria of \$500/kW and \$100,000 / Btu/kWhr. Using these criteria, complementary firing has a performance based evaluation of +\$6.8 million USD.

Capital Cost

A comparison of capital costs associated with the two candidate technologies yields the following relative Capital Cost table:

Cost Component	Supplementary Fired Plant Cost [\$ x 10 ⁶]	Complementary Fired Plant Cost [\$ x 10 ⁶]
SGT-100 package x 2	0	10
Duct Burner System x 2	1.5	0
Black Start Generator Set x 1	2.4	0
Additional HRSG ducting x 2	0	0.25
TOTAL	3.9	10.25
NET ADDITIONAL COST OF COMPLEMENTARY FIRED PLANT		6.35

Net Present Value

This evaluation results in a positive net value of a modest +\$0.4 million USD for the Complementary Firing System as compared to supplementary firing. Consideration of bottoming cycle equipment size/cost reductions was not included in this analysis, but would further favor the Complementary Fired System.

It is acknowledged that this economic analysis provides only a rough and generic assessment of the performance worth of Complementary Firing; project-specific drivers such as fuel costs, ambient temperature ranges, spot market price elevation on hot days, and other nuances would be needed for a complete evaluation.

This basic analysis did not consider the impact of non-fuel operating costs.

CONCLUSIONS

The findings of this paper are that the Complementary Fired System of combined cycle plant power augmentation is a viable method of providing power plant owners a flexible plant loading profile that has the potential to:

- Increase plant revenue by providing the **flexibility** to select optimal power and heat rate combinations given real time dispatch economics.
- Provide added capacity to existing plants at **combined cycle efficiencies for simple cycle installation costs**.
- Provide **peaking capabilities** at heat rates that are significantly lower than a supplementary system, and across a much broader ambient temperature range.
- With a hybrid system, **further increase maximum plant capacity** above the existing supplementary firing plant without negatively impacting plant heat rate or requiring major resizing of pressure and temperature critical systems.

- Decrease high pressure and high temperature parts life fall out by providing peak power at pressures and temperatures that approximate the design values.

Permission for Use

The content of this paper is copyrighted by Siemens Power Generation, Inc. and is licensed to PennWell for publication and distribution only. Any inquiries regarding permission to use the content of this paper, in whole or in part, for any purpose must be addressed to Siemens Power Generation, Inc. directly."