A Concise Guide To Combined Cycle Power Plants

An Online Continuing Education Course for Engineers

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Swapan K. Datta, P.E.

1.0 Introduction

A combined cycle power plant is built on two different heat engines (working on different thermodynamic cycles with different working substances) operating in tandem, producing mechanical energy with overall thermal efficiency better than either of the two constituent engines working alone. In the combined cycle power plant, heat energy is added to only one cycle, the exhaust of which is used for heat recovery by the other cycle.

Various combinations of the energy source (fuel) and heat engines have been tried to build a combined cycle. The most widely used combination is natural gas-fired gas turbines operating in tandem with steam turbines. This type of combined cycle plant is commonly known as NGCC plant. The evolution of NGCC plants has come a long way to its present form of Advanced Combined cycle plant coincidently with the development of the state of the art advanced gas turbines. This course is focused on the NGCC plants in general and advanced NGCC plants in particular.

By virtue of its technical and economic merits, the natural gas-based combined cycle is presently the dominant technology for utility scale electricity generation in the U.S.A.

This course reviews the history of the evolution of the NGCC plants and how it reached the present dominant position in the overall power generation scenario. It explains the superiority of NGCC technology over other power generation technologies based on thermodynamic principles.

The performance of NGCC plants is very much dependent on the ambient condition, which has been explained. The major equipment of a combined cycle plant has been discussed with examples of concept design of NGCC plants with major equipment selection, introduction to the general arrangement of the power block, control philosophy, environmental impacts, etc., concluding with the salient features of a few contemporary advanced combined cycle power plant installations.

2.0 A Brief History

In the 1950s and 1960s, there were various uses of sensible heat in gas turbine exhaust for enhancing the performance of conventional steam power plants like feed water heating or supplying the hot combustion air to a conventional boiler, etc. The first natural gas-fired combined cycle power plant in its present form of combination of the gas turbine cycle and steam cycle was installed in 1961 at "Korneuburg A" power plant in Austria. It was a 75 M.W. plant made up of 2 nos. 25 M.W. B.B.C. type 12 gas turbine and one 25 M.W. steam turbine with a combined cycle thermal efficiency of around 32%. Since then, the evolution of combined cycle plant design had a long way to go to accomplish the present designs of advanced combined cycle plants with thermal efficiency hovering around 62-63%. This was driven mainly by the development of gas turbines with increasing firing temperature leading to the advanced gas turbines with firing temperature around 2600^{0}F and exhaust gas temperature around 1150 - 1200^{0}F and further assisted by the introduction of heat recovery steam generators with welded continuous spiral finned heat exchanger tube and adoption of reheat multiple pressure Rankine cycle with higher steam pressure and temperature.

As reported by the U.S. Energy Information Administration (E.I.A.), the generating capacity of natural gas-fired combined-cycle (NGCC) power plants in the U.S.A. has grown steadily over time, and in 2018, surpassed coal-fired plants as the technology with the most electricity generating capacity in the United States. NGCC plants are also currently responsible for the lion's share of the total utility scale electricity generation in the U.S.A. As reported by E.I.A., of about 4.12 trillion K.W.H. generated in the U.S.A. in 2019, the share of generation by NGCC plants is about 34 %[note-1] compared to about 23.5 % by coal, about 19.7 % by nuclear and about 17.5% by renewable sources.

Note-1: Assuming the generation by NGCC plants is about 90% of total gas-fired generation, as reported by E.I.A. for the year 2018.

3.0 General Description

As shown in Figure-1, the general configuration of a Combined Cycle Power Plant is a gas turbine generator followed by a heat recovery steam generator (HRSG) and a steam turbine generator.

The gas turbine has three sections – air compressor, combustor, and turbine. The compressor draws and pressurizes the atmospheric air, which passes through the combustor, where fuel is burnt to add heat directly to the pressurized air, which then expands in the turbine to generate about 2/3 rd of the total power generated by the combined cycle power plant.

The heat recovery steam generator (HRSG) recovers heat energy from the exhaust of the gas turbine to generate steam to be used by the steam turbine to generate more power

The exhaust steam from the steam turbine is condensed and returned to the HRSG.

The exhaust gas from the HRSG is discharged to the atmosphere through a stack. In most of the plants, a bypass stack is connected through an arrangement of dampers to the gas turbine exhaust duct in order to isolate the HRSG, if required, and discharge the exhaust of the gas turbine through the bypass stack. This arrangement allows operating the plant on a simple cycle, i.e., running only the gas turbine bypassing the steam cycle.

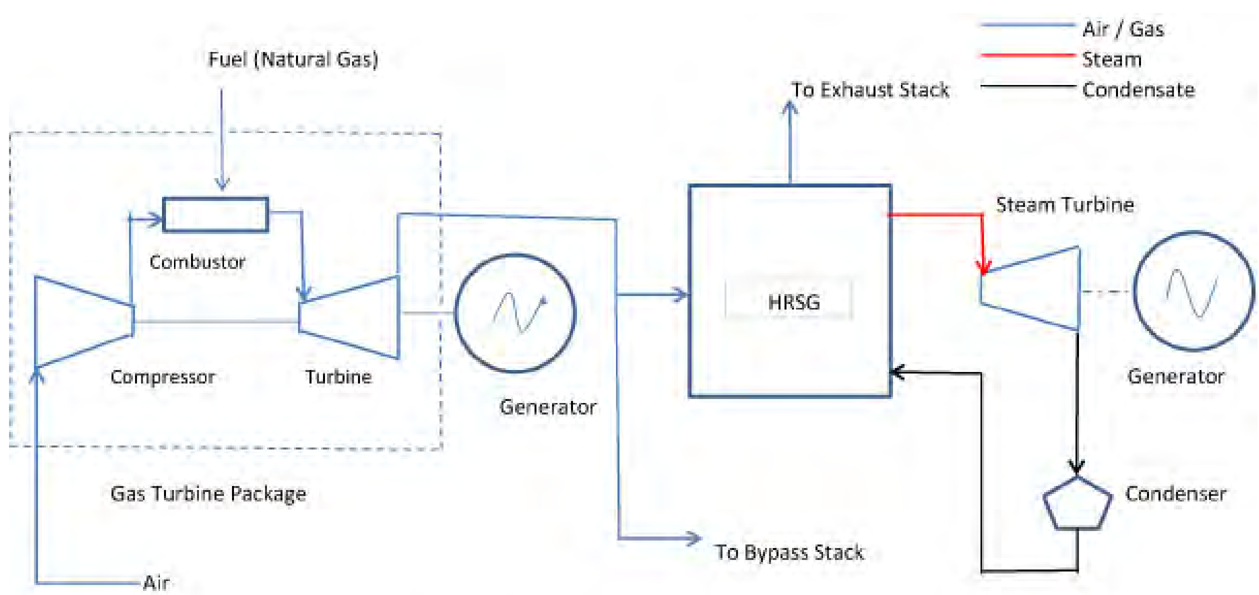


Figure-1 : General Configuration of a Combined Cycle Power Plant

4.0 Advantages of Combined Cycle Power Plant

Followings are the advantages of NGCC technology over other dispatchable energy technologies[Note-2] (technologies making a contribution of at least 10% to the total generation in the U.S.A. have only been considered in this evaluation)

Note-2: Dispatchable energy sources are those, which allow the operator to control the generation as demanded by the grid-like, coal-fired plant, NGCC, nuclear, etc., unlike non-dispatchable sources like solar, wind, etc., generation of which depends on weather and cannot usually be controlled by the operator.

- **Higher thermal efficiency**

The thermal efficiency of an advanced combined cycle power plant built on advanced gas turbines is around 62 - 63 %, compared to 49-50% of a modern, coal-fired ultra super-critical power plant, and 32-35 % of a present-day nuclear power plant.

- **Low capital cost**

Based on the report "Capital cost and Performance Characteristics estimate for utility scale Electric Power Generating Technologies, February 2020" of U.S. Energy Information Administration (E.I.A.), the estimated overnight capital costs[note-3] of representative power plants with different technologies are:

Advanced Combined Cycle Power Plant (NGCC): $958 / K.W.
Ultra Supercritical coal with no Carbon Capture: $ 3676 / K.W.
Ultra Supercritical coal with 30% Carbon Capture: $ 4558 / KW
Advanced Nuclear: $ 6041 / KW

Note-3: Overnight capital cost is the total cost expected to be incurred by the developer, excluding the financing costs.

- **Less construction time and option of phased commissioning**

Average construction time for a combined cycle power plant module is about 24-30 months compared to 48-60 months for a coal plant of comparable capacity and higher for nuclear plants. Also, combined cycle plants have the advantage of phased commissioning, i.e., putting only the gas turbines to operation when ready to generate the simple cycle power (about 2/3 rd of the combined cycle power), much earlier, when the steam cycle is under construction.

- **Much less Carbon Dioxide emission**

  Based on the report "Capital cost and Performance Characteristics estimate for utility scale Electric Power Generating Technologies, February 2020" of U.S. Energy Information Administration (E.I.A.), the estimated Carbon Dioxide emission from representative power plants with different technologies are:

	Advanced NGCC	Coal Fired Ultra Supercritical	
		No CC**	30% CC**
Average CO_2 emission (lb/MWH) (Based on net nominal heat rate)	745	1779	1400

** CC: Carbon Capture

- **Much less real estate requirement**

  Combined cycle power plants require much less space than coal-fired or nuclear power plants of similar size

- **Fast start-up**

  The average cold start-up[note-4] time for a NGCC plant is about 120-140 minutes to reach plant full load, compared to about 450 to 500 minutes required by a coal plant, and much more by a nuclear plant for the same type of start-up. In NGCC plants, however, the gas turbine can be started independently much earlier, thereby generating the simple cycle power, which is about 66% of the combined cycle power.

  Note-4: A cold start-up is typically after a shutdown for a longer period for the turbine and HRSG to become cold.

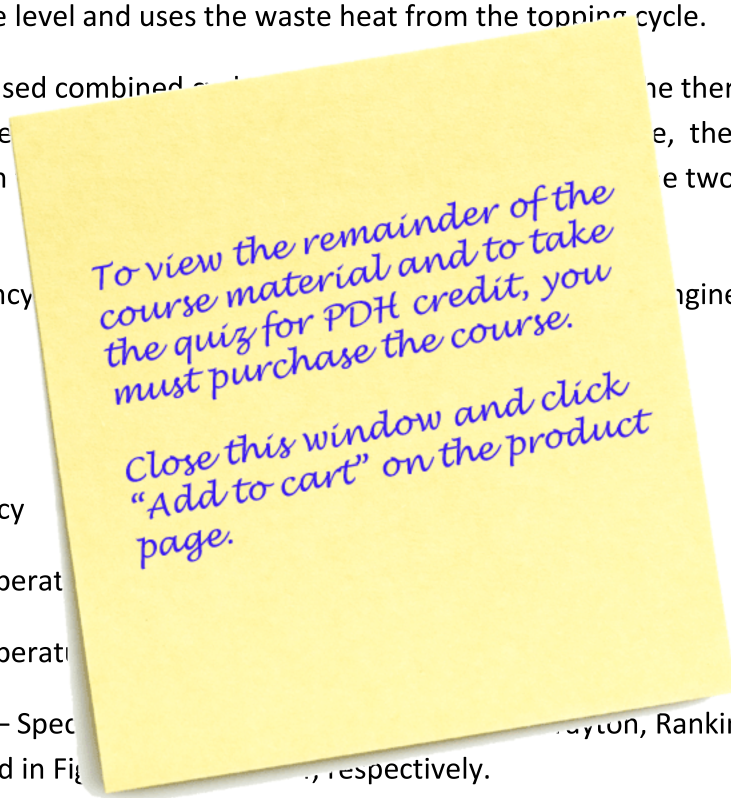
- **Less water requirement**

  In a steam power plant, most of the water is required for cooling in the condenser for condensing the exhaust steam from the steam turbine. A combined cycle power plant having a steam turbine of about 1/3 rd size of other steam power plant of the same size requires much less cooling water.

5.0 Thermodynamic Principles

In a combined cycle power plant, two different thermodynamic cycles are combined to operate in tandem. The goal is to achieve an overall thermal efficiency higher than either of the two constituent cycles. The heat energy is added to the cycle operating at a higher temperature level, called the "Topping Cycle." The other cycle, called the "Bottoming Cycle," operates at a lower temperature level and uses the waste heat from the topping cycle.

In a gas turbine-based combined ... he thermodynamic cycle for the gas turbine ope... e, the thermodynamic cycle for the steam ... e two cycles are coupled through the HRSG.



The Carnot Efficiency ... gine is given by:

$\lambda = 1 - (T_2 / T_1)$

Where,

λ = Carnot efficiency

T_1 = Absolute Temperat...

T_2 = Absolute Temperat...

The Temperature – Spec... ...ayton, Rankine, and Combined cycle are presented in Fi... ..., respectively.