OVERVIEW ON PERFORMANCE ANALYSIS OF COMBINED CYCLE GAS TURBINE (CCGT) POWER PLANT

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ABSTRACT

This paper presents a review of literature on the performance of the Combined Cycle Gas Turbine (CCGT) Power Plant. Focus is placed on the modelling of CCGT and optimization techniques. Available literature emphasizes the importance of CCGT as an effort to increase the efficiency of Gas Turbines (GT) through heat recovery. Using standard models that have wide consensus, the review highlights on various factors that affect the performance of CCGT. Performance, as measured by relative efficiency, is viewed as the ability to effectively use existing resources optimally. The review notes several optimization techniques based on existing and new models including operational, design, and environmental factors.

Keywords: CCGT, turbine, power, efficiency, model, performance.

INTRODUCTION

The increase in demand for energy globally is extensively documented. Several factors have been associated with such an increase. For example, Kumar, *et al*. (2007) attributed increased energy demand to economic growth, significant population growth, and urbanization. Similar views have been considerably noted in the literature (e.g.; Jassim, *et al*, 2015; Rai *et al*. 2013; Nayak & Mahto, 2014). CCGT power plants are an essential part of the global energy production sector. Rai., *et al*. (2013), for example, mentioned that electrical energy was a basic requirement for the sustenance and continued development of society and that CCGTs played a key role in advancing electrical generation. The central role of electricity generation can be further underscored by the ever-increasing trend in energy demand that has been mentioned in the study by Nayak and Mahto (2014), for example.

The current paper reviews studies on combined cycles gas turbines (CCGT) to explore the modelling of CCGT, optimization techniques for CCGT, and associated performance. Overall, CCGT and Combined Cycle Power Plants (CCPP) have been used interchangeably to mean the same thing in literature (e.g., Dev, *et al*, 2015; Rai J., *et al*., 2013; Rai J., *et al*. 2013). Fundamentally, CCGT can be viewed as a system with two cycles; the Brayton cycle (Gas Turbine) and the Rankine cycle (Steam Turbine) to increase overall plant efficiency (Ibrahim & Rahman, 2012; Nayak & Mahto, 2014; Tiwari, Islam, & Khan, 2010).

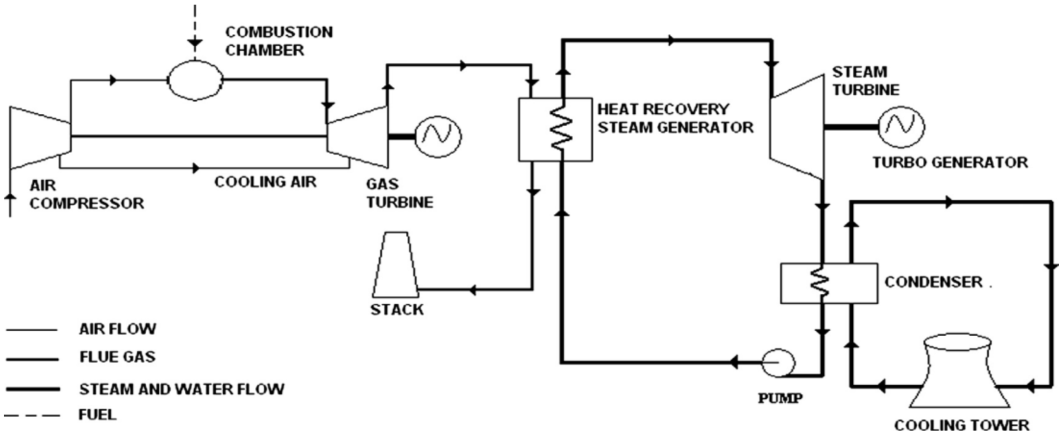


Figure-1. Schematic Illustration of a CCGT.

The improvement achieved by CCGT compared to GT is illustrated by Rai., *et al.*, (2013). That is, in their study, it is mentioned that the efficiency of a gas turbine which ranges from 28% to 33% can be raised to about 60% by recovering some of the low-grade thermal energy from the exhaust gas for the steam turbine process. Accordingly, following the efficiency benefits, CCGT has been extensively adopted. For example, Mattos, *et al*. (2016) noted that because a power plant operating in a combined cycle achieves high values of thermal efficiency compared with other available configurations, CCGT has been extensively adopted for power generation. Studies have demonstrated that they are characterized by better thermo-dynamic, economical, ecological, and operating indexes (e.g., Dev, *et al*, 2015).

Modelling of Combined Cycle Gas Turbine

There are several different combined cycle configurations and control variations available from various manufacturers as commented by Kumar (2007). Typically, and as mentioned in the study according to the Working Group on Prime Mover and Energy Supply Models for System Dynamic Performance Studies (1994), CCGTs could be based on a range of models. For instance, a study presented by Horlock (2003) (see Figure-2) explored various GT models noting the varying efficiencies. It may be prident to underscore the differences in optimim operating ration, for instance, as a notable difference among the turbines. However, it also evident that some performed better than other overall. Such performance, nonetheless, is subject to other confounding factors, abient temperature for example, among other factors (e.g., Jassim, *et al*, 2015; Tiwari, *et al*, 2013).

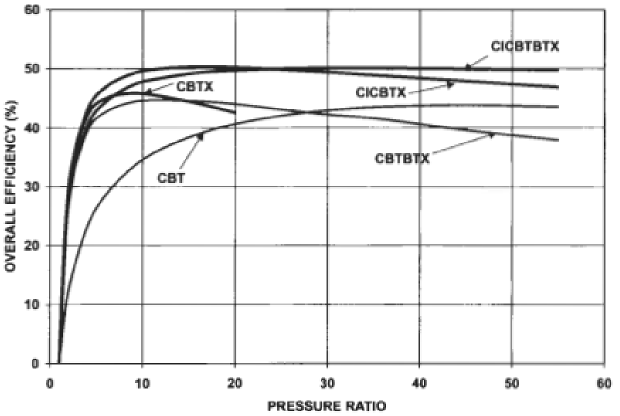


Figure-2. Overall efficiencies of several irreversible gas turbine plants (with T, = 120O^{0}C) Source: Adapted from Horlock (2003).

Dev (2015) described CCGT as multifaceted and intricate instructure. Also, as highlighted in the presentation by Shalan, Hassan, *et al* (2010), there has been a considerable growth in GT technology resulting in a range of models. Noting that Gas Turbines are an essential part of CCGT, it is possible to appreciate the extent of the possible combinations available for CCGT models. In a model of the Gas Turbine by Kunitomi, *et al*. (2001), it was mentioned that Gas turbines produce approximately two-thirds of the total power output of a typical combined-cycle power plant. The case, in essence, rationalizes the continued need for understanding and optimizing emerging models of CCGTs.

However, there appears to be a fundamental understanding of CCGT. Studies according to Rai., et al. (2013), Nayak & Mahto, 2014)and others presented a consensus on the basic model of a CCGT power plant. That is, it consists of a gas and steam turbine, a compressor, a combustor, a waste heat recovery boiler, and a generator. As described in the introduction, models on CCGT are based on the basic structure of CCGT with various modifications. Some of the models that have been engaged in the study of CCGT include the W.I Rowen model of the gas turbine (e.g., Kunitomi, *et al*., 2001; Rai J., Hasan, Arora, & Garai, 2013; Shalan, Hassan, & Bahgat, 2010), Detailed model Shalan, Hassan, & Bahgat, 2010), a model developed by the Working Group on Prime Mover and Energy Supply Models for System Dynamic Performance Studies (1994), GGOV1 Model, IEEE Model. 5. CIGRE Model, Frequency-Dependent (FD) Model, and the Detailed Model (Shalan, Hassan, & Bahgat, 2010).

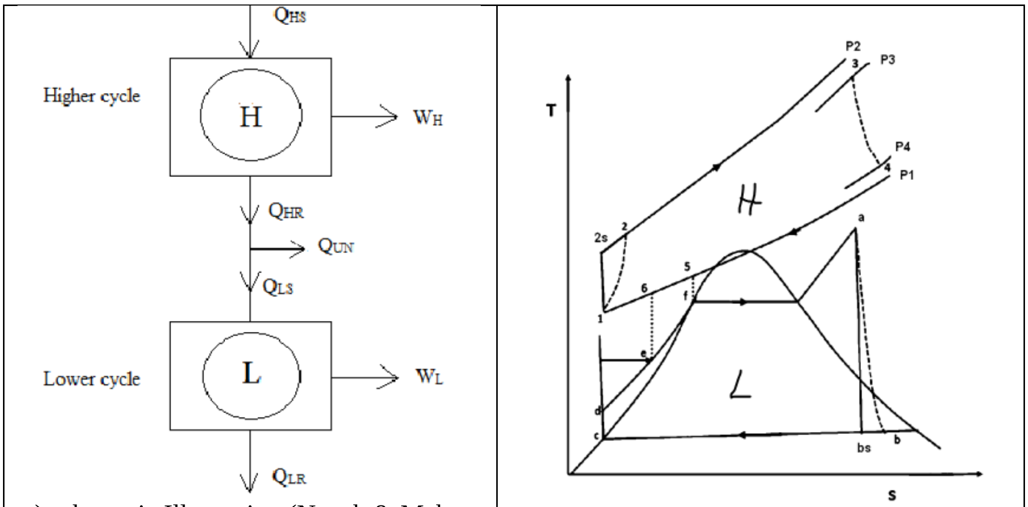
While the mentioned models present options that have gradually been improved from the initial Rowen-I model. Assessments and comparisons of the models has indicated limitations of each. For instance, in as assessment of Shalan, *et al* (2010) where a comparative study of the models was conducted, it was concluded that the models had different levels of accuracy. Nonetheless, they tended to suit different applications and such accuracy appeared to vary with application as well.

Optimization Techniques

Now that the objective of power plants, including the subject power plant of this review, is to generate power, the central focus of operation and research has mostly been towards optimization of power generation. In the current review, it has been extensively observed that studies on optimization have based their measure on system efficiency. That is, as noted by Dev, *et al* (2015), for example, a system fails to be efficient when it fails to use existing resources optimally. The case brings about the effect of the immediate environment on the performance of power plants as extensively interrogated in the highlighted literature (e.g., Rai *et al*. 2013; Tiwari, 2013; Tiwari, 2010). Nonetheless, while the current review looks into different models and highlights several optimization techniques, it is worth noting, as illustrated by Dev, *et al* (2015), for example, that optimal utilization of resources by CCGT is a function of a range of variables including design, manufacturing, construction, operation, and maintenance of subsystems and equipment of the CCGT system.

Primarily, it is worth noting that CCGT systems are an effort to optimize power plants. The reviewed studies have suggested that a CCGT intends to increase overall plant efficiency. Mattos, *et al.* (2016), for instance, noted that power plants operating in a combined cycle present higher thermal efficiency. An earlier study on the performance of Gas turbine-based plants also noted that CCGT could achieve higher energy efficiencies. The case has been extensively collaborated in the studies by Rai., *et al*. (2013) and Nayak and Mahto (2014) which touched on the performance of CCGTs. The optimization of the CCGT is based on the heat recovery that is facilitated by the bottoming cycle. For instance, Nayak and Mahto

(2014) noted that the heat rejected by the higher temperature cycle is recovered and used by a lower temperature cycle to produce additional power to improve overall efficiency (see Figure-3).



a) schematic Illustration (Nayak & Mahto, 2014)

b) T-S Diagram(Tiwari, et.al 2013)

Figure-3. An illustration of the basic thermodynamics of a CCGT. Source: Adapted from (Nayak & Mahto, 2014).

From the illustrations in Figure-3, Work for the two cycles could be represented as;

$$WGT = mgcpg(T3 - T4) - macpa(T2 - T0)$$

And;

$$WST\ (\text{Lower Cycle}) = ms(ha - hbs)\eta st$$

Several techniques have been explored to optimize the CCGT including interventions to influence the inputs such as the ambient temperature and the specific cycles. Kumar, Krishna, & Raju (2007) explored the heat recovery steam generator (HRSG) of the CCGT. In their study that entailed thermodynamic analysis, it was established that the configuration of the HRSG influenced the efficiency. That is, Dual pressure HRSG was found to offer better efficiency and less irreversibility compared to single pressure HRSG. The pressure difference was seen as a significant factor in optimizing performance.

In a study by Tiwari, *et al.* (2010) the Air Bottoming Cycle (ABC) was explored as a replacement for the heat recovery steam generator and the steam turbine of the conventional combined cycle plant. The study indicated that such a replacement had the potential to improve the efficiency of up to 80%, a gain of up to 68% based on the subject system.

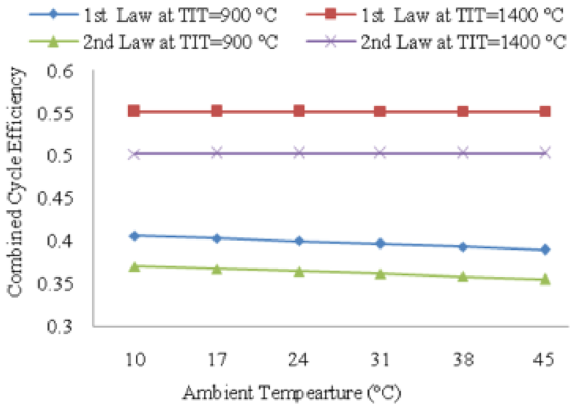
The mediate environmental characteristics were also adversely mentioned in the optimization studies. The effect of ambient temperature on performance, for example, is explored in several studies reviewed (e.g., Tiwari, Hasan, & Islam, 2013; Jassim, Zaki, Habeebullah, & Alhazmy, 2015). Emphasis is placed on the role of temperature difference in work done and its consequent effect on overall efficiency (e.g., Tiwari, *et al* 2013; Tiwari, *et al*, 2010).

$$\text{Work done} = \text{Mass flow rate} * \text{Specific heat at constant pressure } (\Delta T) \quad (1)$$

In simulating the performance of GT in hot ambient temperatures, Jassim, Zaki, Habeebullah, & Alhazmy (2015), used a simulated model to assess the effect of cooling the intake air to enable better efficiency. The study found an overall improvement in output power due to the refrigerating intake of air. In a similar study that incorporated the environmental conditions in optimizing CCGT, Ibrahim and Rahman (2012) used a MATLAB simulation to demonstrate the performance of GT and CCGT. The study demonstrated a positive effect of compression ratio on efficiency. Output power increased with an increase in peak compression ratio, lower ambient temperature, and higher turbine inlet temperature.

Combined cycles gas turbines (CCGT) are extensively used to acquire a high-efficiency power plant. As noted before, CCGTs are designed to integrate two cycles- the Brayton cycle and Rankine cycle to increase overall plant efficiency as illustrated in Figure-2.

The efficiency of a gas turbine has been observed to range between 28% to 33% and can be raised to about 60% by recovering some of the low-grade thermal energy from the exhaust gas for the steam turbine process (Rai J. N., *et al*., 2013). However, as adversely mentioned in the reviewed literature, the location of the power plant plays a major role in its performance. For example, in their study Tiwari (2013) investigated the influence of turbine inlet temperature of combined cycle efficiency (Figure-4). The study established a significant difference on efficiency especially when analysis was based on the second law of thermodynamics.



TIT = Turbine inlet temperature

Figure-4. Illustration of CCGT efficiencies based on ambient temperature. Source: Tiwari, *et al* (2013).

CONCLUSION

While commenting on the nature of CCGT power plants, Soares (2007) (As cited in Mattos, *et al.*, 2016), noted that attention on CCGT resulted in considerable improvements in the overall performance and efficiency of CCGT systems. The case can be demonstrated by the highlighted varied models that exhibited notable variations in performance. Based on the review of the different models and optimization efforts highlighted in this review, it is possible to note that modeling and optimization of CCGT remains an ongoing effort. While available, and widely adopted, models provide a basis for the study of CCGT, notable improvements in existing models continue to be needed.

Notably, it was possible to establish that a range of models has been developed and widely adopted. A key question, and for the sake of future development of CCGT and research could be on the optimal model. While it was evident that the development of new models tended to gradually address possible limitations of previous models, it was possible to observe, as indicated in this review, that CCGTs remain complex. Accordingly, the best model is as good as the immediate objective. Nonetheless, the detailed model appears to provide a more comprehensive, yet still not exhaustive, representation of the CCGT system.

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Nomenclature

ABC	Air Bottoming Cycle
a	Air
c	Specific heat capacity
CBT	Curved Blade Turbine
CBTX	Simple Brayton cycle with regeneration
CICBTX	Turbine with two compressors and one turbine
FD	Frequency Dependent
g	Gas
GT	Gas Turbine
h	Enthalpy
H	Heat
HRSG	Heat Recovery Steam Generator
L	Lower cycle
$\dot{m}$	Mass flow rate
n_{st}	Efficiency of Steam Turbine
P	Pressure
Q_{HR}	Heat rejected by the higher cycle
Q_{HS}	Heat supplied to the higher cycle
Q_{LR}	Heat rejected by the lower cycle
Q_{LS}	Heat Supplied to the lower cycle
ST	Steam Turbine
T	Temperature
TIT	Turbine inlet temperature
UN	Unused Heat
W	Work output
WH	Work done by higher cycle
WL	Work done by lower cycle
ΔT	Change in Temperature