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The optimum performance of the combined cycle power plant: A comprehensive review

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ABSTRACT

Improving the efficiency and reducing the pollutants are the critical concerns for any design of power generation plants. Identifying the characteristics of the Combined Cycle Gas Turbine (CCGT) system and locating the optimum operation conditions via simulation models are irreplaceable route due to the huge system and the impossibility of experimental investigations. To that end, this paper presents modelling analysis with the aim of enhancing the performance and optimization conditions seeking of the (CCGT) power plant with various configurations. The developed simulation models are integrated to encapsulate thermal analysis according to thermodynamics principles, optimization techniques, error analysis, and performance metrics assessment of the various CCGT system configurations using the MATLAB 10A software. A statistical tool, ANOVA, is utilized to assess the results and to develop correlations between the power outputs and performance metrics of the CCGT plants. The new correlations which are developed within the frame of this work are of acceptable accuracy for all the considered range of the simulation data. The coefficient of determination (R^2) is calculated as 0.985 which is considered satisfactory as well. The validity of the correlations is investigated against actual performance and operation data extracted from an actual power generation plant, the MARAFIQ CCGT plant in KSA. Consequently, an error analysis which is carried out considering the actual operation and performance records of MARAFIQ CCGT plant as a benchmark proved the validity of the model. An error of about 0.8104% is found. The operation parameters and performance metrics of the CCGT plant are ultimately assessed against variations of selected parameters via the developed model. Adaptive Neuro-Fuzzy System (ANFIS) is used as an optimization technique. The highest attained power output and thermal efficiency were 1540 MW and 61%, respectively. Turbine inlet temperature is found to be the key parameter for the optimum performance (power and thermal efficiency). The models developed in this work are a powerful tool for analyzing and optimising CCGT which take the place of very expensive and strenuous experimental works.

1. Introduction

The CCGT plants development nowadays is the result of decisions taken by politicians since 40 years ago [1]. Several countries have taken the oil out of power generation as a reaction to the 1973 oil crisis and due to the increased knowledge about the environmental concerns [1]. The CCGT plants stand for the most efficient technology for energy conversion, and the most-wanted option selected to satisfy the increased demand for electric energy in the world [2]. The important target for all the heavy-duty industrial gas turbine (GT) manufacturers was achieving an overall thermal efficiency of 60% in the CCGT plants under ISO conditions [1]. The efficiency improvement term encapsulates reducing both the costs and the harmful emissions. Attaining higher overall thermal efficiency of the CCGT necessitates optimising

Abbreviations: ANFIS, Adaptive Neuro-Fuzzy Inference System; *CC*, Combustion chamber; *CCGT*, Combined-cycle gas turbine; *DA*, De-aerator; *GT*, Gas turbine; *HP*, High pressure; *HPST*, High-pressure steam turbine; *HRSG*, Heat recovery steam generator; *IP*, Intermediate pressure; *IPST*, Intermediate-pressure steam turbine; *LP*, Low pressure; *LPST*, Low-pressure steam turbine; *LHV*, Lower Heating value; *RH*, Reheat section; *SFC*, Specific fuel consumption; *ST*, Steam turbine; *SGTCC*, Simple gas turbine combined cycle; *TIT*, Turbine inlet temperature; *TTD*, Terminal temperature difference

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Nomenclature

C_{pa}	Specific heat of the air (kJ/kg K)
C_{pf}	Specific heat of the fuel (kJ/kg K)
C_{pg}	Specific heat of flue gas (kJ/kg K)
F	Fuel-air ratio
$\dot{m}_a$	Air mass flow rate (kg/s)
$\dot{m}_f$	Fuel mass flow rate (kg/s)
$\dot{m}_g$	Mass flow rate of the exhaust gases through the gas turbine (kg/s)
$\dot{m}_w$	Water mass flow rate (kg/s)
P	Pressure (bar)
Q_{add}	Heat supplied (kJ/kg)
Q_{av}	Heat available with exhaust gases from gas turbine cycle (kJ/kg)
Q_{cond}	Heat rejected from the condenser (kJ/kg)
P	Net power output of the turbine (MW)
r_p	Pressure ratio
T	Temperature (K)
T_1	Compressor inlet air temperature (K)
T_a	Average temperature (K)
T_f	Temperature of the fuel (K)
T_s	Saturation steam temperature (K)
T_{w1}	Temperature of water entering the economizer (K)
W_c	Work of the compressor
W_{Gnet}	Net-work of the gas turbine (kJ/kg)
W_t	Shaft work (kJ/kg)
W_{net}	Net work of the turbine cycle (kJ/kg)
w_p	Work of the pump
w_{snet}	Net work for the steam turbine power plant (kJ/kg)
W_{st}	Work of the steam turbine (kJ/kg)

Greek symbols

η_t	Isentropic turbine efficiency
η_{th}	Gas turbine efficiency
γ_a	Specific heat ratio of air
γ_g	Specific heat ratio of gases
Ε	Effectiveness of the regenerative heat exchanger
η_{all}	The overall thermal efficiency
η_C	Isentropic compressor efficiency
η_m	Mechanical efficiency of the compressor and turbine

the entire plant, and the three major components: the GT, The Heat Recovery Steam Generator (HRSG) and the Steam Turbine (ST) [3]. However, among the three components of the CCGT plants, the performance of the GT comes into first as the predominant influencer on the performance; with which plant efficiency can touch the 60% target and even more [4,5].

The CCGT power plants represent an attractive way to produce electrical energy from the primary energy resources. The implement of the CCGT performance analysis is a necessity to keep the plant working efficiently [6]. Ersayin and Ozgener [6], conducted a study on the analysis of CCGT performance based on the first law of thermodynamics. The analysis depended on the actual data which collected from the control room of the CCGT power plants. Parametric analysis and the calculations of the energy efficiency of plant components were performed. The results showed that the energy efficiency was about 56%.

Kaviri et al. [7] examined the effect of mass flow rate and HRSG inlet gas temperature on the cycle efficiency. They observed that the increase of the exhaust gases temperature which enters to the HRSG until 650 °C led to an increase in the thermal efficiency. Beyond this temperature, the efficiency was dropped. Kaviri et al. [8] investigated the multi-objective optimization of a combined cycle power plant. They had been indicated the more significant design parameters that affected plant efficiency were the compressor pressure ratio, inlet gas turbine temperature, and pinch point temperatures. Sanjay [9] has examined the impacts of the difference of cycle parameters on rational efficiency and component exergy destruction of the combined cycle power plant. According to his findings, the HRSG gas inlet temperature was the important parameter on the cycle performance.

The CCGT plants are globally recognized as the most efficient converter fossil fuel to electricity. The performance has been enhanced by the growing usage of these plants. The turbine inlet temperature is increased and thus, it was suggested [10]. The CCGT plants have developed on the experience built up in the past 40 years [11]. Owing to the existence of two different thermal power cycles that are joined through the heat recovery steam generator (HRSG), the CCGT plant has been designed intrinsically [12,13]. The best incorporation between the power units will determine the performance of the CCGT system [14–16]. The HRSG component of the CCGT cycle can be made on order particularly for each GT unit, while the GT and the ST (steam turbine) can be selected from among the set of commercially available range plant [17–19].

Khaliq and Kaushik [20] defined the thermodynamic methodology which used for combustion reheat GT cogeneration performance investigation through the energetic efficiency. In addition, the effects of temperature, steam pressure and pinch point were evaluated on the CCGT plant's thermal efficiency that was used in the reheat section and HRSG design. Woudstra et al. [21], show the effect of increasing the temperature of pinch point on increasing the power to heat ratio and decreasing thermal efficiency. Zhang et al. [12] show significant improvement of including reheat section on fuel saving, thermal efficiency, power output and heat production. Thamir and Rahman [22–25] proposed the thermodynamic methodology to measure the performance of different selections of the CCGT power plants and comparison of the combined cycle power production systems. Atmaca [26] implemented the thermodynamic analysis on combination of the natural gas's basic cycle and cogeneration plant and showed that increasing power to heat ratio will decrease overall thermal efficiency and the energy usage factors. According to Bassily [27], the GE Stage 107H and Mitsubishi M501H were optimized as a commercial triple-pressure with reheat CCGT plants in combination with operating condition. Compression ratio, stack temperature and cooling steam ratio are set as limitations on the operation conditions. The overall thermal efficiency and power output of the GT cycle were optimized at varying temperature values of turbine inlet which showed that the CCGT plants performed better power output at 400 MW [28].

The location conditions mostly relative-humidity, atmospheric pressure and ambient temperature of the air of the place where the CCGT power plant installed had strong significant on the operation of the CCGT. Among these parameters, the ambient temperature had the greatest effect during operation on the performance divergence [29–34].

Erdem and Sevilgen [35], determine the effect of the ambient conditions on the actual gas turbine performance variation. For this aim, seven climate locations of Turkey and two gas turbine models are considered in this purpose. They investigated the influence of ambient temperature on the electricity power generation and consumption of the fuel of the gas turbine cycle [35]. The results show that, the loss is about 2.87–0.71% of the electricity generation, compared to the annual production at standard conditions rate in hot locations. When the temperature increased higher than 15 °C the loss in the power generations was increased in all locations. Additionally, with cool the inlet temperature until 10 °C the electricity production increases for about 0.27–10.28%.