EFFECT OF AMBIENT TEMPERATURE ON THE PERFORMANCE OF COMBINED CYCLE POWER PLANT WITH COOLING SYSTEM IN A SUBTROPICAL REGION

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ABSTRACT

The climate conditions have a powerful influence on combined cycle power plant performance as its known. Total output power and overall thermal efficiency of the power plant dropping under the high ambient temperatures that often occur during the hot days. This is a major drawback for combined cycle power plant operated in a subtropical region. In the Middle East where this study was carried out, the ambient temperature typically varies between (15C) and (45C). The Plant has been studied consist of three gas turbines with total power (535MW) and three triple-pressure heat recovery steam generators, addition one steam turbine with (345 MW) output power. The overall thermal efficiency of power plant is (57.7%). In this study, combined cycle power plant was used for assessment of the performance with the changes in ambient air temperature. Two approaches were used to study this phenomenon. Firstly, the performance parameters were calculated by using actual data acquired by the operation history of the power plant. Secondly, the performance was analyzed using thermodynamic principles. Then results of the two approaches were compared and optimizing using RBFNN method. Cooling the gas turbine inlet air can improve the power plant performance substantially. This occurs due to the cooled air is denser, giving the compressor a higher mass flow rate and resulting in increased output power and efficiency of the power plant. Single effect LiBr absorption chiller proposed as a cooling system to cool the ambient air temperature at (15 C). The average reduction in power output per degree Celsius is about (1.82 MW). Cooling of inlet air from (45°C) down to (15°C) would increase the power output around (50.04MW). Where every decline in temperature by (10°C) adding to the total output power of (16 MW). The average reduction in the overall thermal efficiency per degree Celsius is about (0.217%). In addition, the cooling of inlet air from (45°C) down to (15°C) would increase the overall thermal efficiency around (6.091%). Where every decline in the temperature by (10°C), that increases the overall thermal efficiency around (2.03%). The results of using this cooling technique are increasing the total output power and overall thermal efficiency to (875 MW), (58%) respectively. The effect of using radial basis function neural network (RBFNN) technique give the average deviation about (1.2%) and (1.7%) for the power output and thermal efficiency respectively.

ABSTRAK

Keadaan iklim mempunyai pengaruh yang kuat ke atas gabungan prestasi loji janakuasa kitar seperti yang diketahui. Jumlah kuasa output dan kecekapan keseluruhan haba loji kuasa menjatuhkan bawah suhu ambien yang tinggi yang sering berlaku pada hari-hari panas. Ini adalah kelemahan utama bagi loji tenaga kitaran beroperasi di kawasan yang subtropika. Di Timur Tengah di mana kajian ini dijalankan, suhu ambien biasanya berbeza-beza antara (15C) dan (45C). Loji telah dikaji terdiri daripada tiga turbin gas dengan jumlah kuasa (535 MW) dan tiga penjana pemulihan haba wap tekanan tiga kali ganda, tambahan satu turbin stim dengan (345 MW) kuasa keluaran. Kecekapan keseluruhan haba loji kuasa (57.7%). Dalam kajian ini, loji tenaga kitaran telah digunakan untuk penilaian prestasi dengan perubahan dalam suhu udara ambien. Dua pendekatan telah digunakan untuk mengkaji fenomena ini. Pertama, parameter prestasi dikira dengan menggunakan data sebenar yang diperolehi oleh sejarah operasi loji janakuasa. Kedua, prestasi dianalisis menggunakan prinsip termodinamik. Maka keputusan kedua-dua pendekatan telah dibandingkan dan mengoptimumkan menggunakan kaedah RBFNN. Penyejukan udara masuk turbin gas boleh meningkatkan prestasi loji kuasa dengan ketara. Ini berlaku kerana udara sejuk adalah lebih padat, memberikan pemampat kadar aliran jisim yang lebih tinggi dan menyebabkan peningkatan kuasa keluaran dan kecekapan loji kuasa. Single kesan LIBR penyejuk penyerapan dicadangkan sebagai sistem penyejukan untuk menyejukkan suhu udara ambien di (15 C). Pengurangan purata kuasa output per darjah Celsius adalah kira-kira (1.82 MW). Penyejukan udara masuk dari (45 ° C) ke (15 ° C) akan meningkatkan output kuasa sekitar (50.04MW). Di mana setiap penurunan suhu dengan (10 ° C) menambah kepada jumlah kuasa keluaran (16 MW). Pengurangan purata kecekapan haba keseluruhan per darjah Celsius adalah kira-kira (0,217%). Di samping itu, penyejukan udara masuk dari (45 ° C) ke (15 ° C) akan meningkatkan kecekapan keseluruhan haba sekitar (6,091%). Di mana setiap penurunan suhu oleh (10 ° C), yang meningkatkan kecekapan keseluruhan haba sekitar (2.03%). Keputusan menggunakan teknik ini penyejukan semakin meningkat jumlah kuasa keluaran dan kecekapan haba keseluruhan (875 MW), (58%) masing-masing. Kesan penggunaan rangkaian neural teknik jejarian fungsi asas (RBFNN) memberi sisihan purata kira-kira (1.2%) dan (1.7%) untuk output kuasa dan kecekapan haba masing-masing.

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NOMENCLATURES

List of Symbols

Symbol	Meaning and units
AFR	Air-fuel ratio
C_{pa}	The specific heat of the air (kJ/kg.K)
C_{pf}	The specific heat of the fuel (kJ/kg.K)
C_{pg}	The specific heat of flue gas (kJ/kg.K)
f	The fuel-air ratio
h	Enthalpy (kJ/kg)
h_{4f}	The heat loss factor in the heat recovery steam generator
LHV	The lower heating value (kJ/kg)
$\dot{m}_a$	The air mass flow rate (kg/s)
$\dot{m}_f$	The fuel mass flow rate (kg/s)
$\dot{m}_g$	The mass flow rate of the exhaust gases through the gas turbine (kg/s)
P	The net power output of the turbine (MW)
p	Pressure (bar)
p_1	Compressor inlet pressure (bar)
p_2	Compressor outlet air pressure (bar)
Q_{add}	The heat supplied (kJ/kg)
$Q_{available}$	The heat available with exhaust gases from gas turbine cycle (kJ/kg)
$Q_{condenser}$	Heat rejected from condenser (kJ/kg)
r_p	Pressure ratio
Q_{ex}	Heat of exhaust gases (kJ/kg)
SFC	The specific fuel consumption (kg/kW.h)
T	Temperature (K)
T_1	Compressor inlet air temperature (K)
T_2	Compressor outlet air temperature (K)
T_{2s}	The isentropic temperature of outlet compressor (K).

T_a	The average temperature $(T_2+T_1)/2$ (K)
T_{ap}	The approach points (K)
T_f	The temperature of fuel (K)
T_{pp}	The pinch point (K)
T_s	The saturation steam temperature (K)
T_{w1}	The temperature of water entering the economizer (K)
T_{w2}	The temperature of water entering the evaporator (K)
v_f	Specific volume of the water (m^3/kg)
W_{comp}	The work of the compressor (kJ/kg)
W_{GTnet}	The net work of the gas turbine (kJ/kg)
W_{pump}	The work of the pump (kJ/kg)
W_{STnet}	The work net of the steam turbine cycle (kJ/kg)
W	The work of the steam turbine (kJ/kg)
W_{ST}	The shaft work of the turbine (kJ/kg)

Greek Symbols

Symbol	**Meaning**
ε	Effectiveness of the regenerative heat exchanger
ρ	Density (kg/m^3)
k	Specific heat ratio
k_{air}	Specific heat ratio of air
k_{gas}	Specific heat ratio of gases
η	Efficiency
η_{comp}	Isentropic compressor efficiency
η_{chp}	The high-pressure compressor efficiency
η_{clp}	The low-pressure compressor efficiency
η_{HPT}	The high-pressure turbine efficiency
η_{LPT}	The low-pressure turbine efficiency
η_{mech}	The mechanical efficiency of the compressor and turbine
η_p	The water pump efficiency

η_{ST}	The steam turbine efficiency
$\eta_{overall}$	Overall efficiency of CCPP
$\eta_{th,Brayton}$	Thermal Brayton cycle efficiency
η_{th}	The thermal efficiency of the gas turbine

Subscripts

Symbol	**Meaning**
1,2…etc	State number
a	Air
add	Added
ap	Approach point
av	Average
comp	Compressor
cond	Condenser
f	Fuel
g	Gases
GTnet	Gas turbine net work
HP	High pressure
IP	Intermediate pressure
LP	Low pressure
p	pump
pp	Pinch point
s	Saturated steam
STnet	Steam turbine work net
ss	Superheated steam
ST	Steam turbine
w	Water
w1	Inlet water to economizer
w2	Inlet water to evaporator

LIST OF ABBREVIATIONS

Comp	Compressor
C.C	Combustion chamber
CCPP	Combined cycle gas turbine power plant
D	Drum
GT	Gas turbine
HE	Heat exchanger
HPST	High pressure turbine
HRSG	Heat recovery steam generator
IEA	International Energy Agency
IP	Intermediate pressure
IPST	Intermediate pressure turbine
ISO	International standards organization
LHV	Lower Heating Value
LP	low pressure
LPST	Low pressure turbine
SFC	Specific fuel consumption
ST	Steam turbine
TIT	Turbine inlet temperature

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTIONS

When the industrial revolution is starting, people become more and more dependent on hydrocarbon fuels for the generation of power. Now around (85%) of the energy requirements of the almost counties are supplied by fossil fuels. The increasing combustion of fossil fuels and associated carbon dioxide (CO_2) emissions are creating concerns about climate change. One of the most significant and innovative solutions that reduce greenhouse gas emissions and an increase in generated net power with characterized as high efficiency is a combined cycle power plant (CCPP).

Grows energy consumption of the world marketed by (49) percent from (2007 to 2035) (IEO, 2010). The total energy use in the world rises from (495) quadrillions British thermal units (Btu) in (2007) to (590) quadrillions Btu in (2020) and (739) quadrillions Btu in (2035) as shown in Figure 1.1 (IEO, 2010) an increase of over (6%) per annum (Sepehr Sanjay, 2011). The global economic downturn which started in (2007) and non-stop until (2015) has had a profound shock on world energy requirement in the near expression. With the fall in demand among both manufacturers and consumers came a decline in total global marketed energy consumption by (1.2) percent in (2008) and by (2.2) percent in (2009) (IEO, 2010).

The average annual growth in electricity power demand in the world, over the past twenty years, was approximately 6 % and forecast for the next five years is 6% per annum (Marroquin, 2010). Furthermore, the rate of electricity consumption was observed to be higher than the rate of production and in particular during the summer season where the high peak of electricity demand prevails.

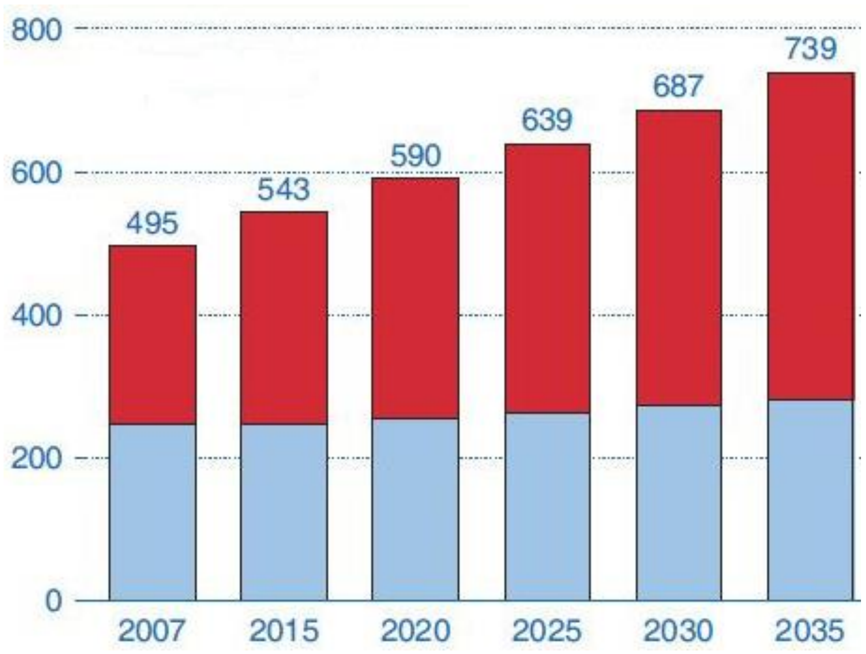

Fig 1.1: World marketed energy consumption, 1990-2035.
International Energy Outlook (IEO), 2010. *U.S. Energy Information Administration*, (http://www.eia.doe.gov/oiaf/ieo/world.html).

Due to The combined cycle power plant flexibility in the production of power and relatively inexpensive capital costs, in recent years, it becomes more popular used. This flexibility in the application of combined cycle and improved efficiencies can be achieved. This flexibility is imperative (D. Mahto, 2012). Through the design of the cycle, can operating the gas turbine without operation of the steam turbine. Additionally, parts of the steam that generated from the Heat Recovery Steam Generator (HRSG) can be used for other processes like cooling by vapor absorption chiller, distillation the sea water and other application, also, to run the steam turbine. Furthermore, by burning additional natural gas in the HRSG can increase the power generation during hours of peak demand. However, the gas and steam turbines have individually efficiencies around (40%), while, and operated together in the combined cycle system, thermal efficiencies can attain 60% of the LHV (D.L. Chase 2000).

The combined cycle power plant (CCPP) combines two thermodynamic cycles, the Rankine cycle for steam turbine and the Brayton cycle for a gas turbine, to generate power efficiently. And these combinations Brayton cycle of the gas turbine and Rankine cycle the steam power system complement each other to form efficient combined-cycles. The Brayton cycle has high source temperature and rejects heat at a temperature that conveniently used as the energy source for the Rankine cycle. In other words, practically in the gas turbine not converted all the energy that come from the combustion of fuel (Natural Gas and Air) to shaft power. The residual energy released as waste heat in the flue gas, the exhaust heat may be used in various ways. If exhaust heat is used to produce steam in a waste heat boiler for a steam turbine, with the object of augmenting the shaft power produced, the system is called combined gas/steam cycle. The only limitation is the exhaust (stack) temperature (Çengel & Boles, 2008)

The most commonly used working fluids for combined cycles are air and steam; other working fluids (organic fluids, potassium vapor, mercury vapor, and others) have been applied on a limited scale. Combined-cycle systems that utilize steam and air working fluids have achieved widespread commercial application (Çengel & Boles, 2008). Usually, in typical plant drive combine one or more than gas turbines, almost cases run three gases turbines. Also consisting of other major components are steam turbines, heat recovery steam generators (HRSG), and generators to produce electricity.

The fuel used in the combined cycle power plant is natural gas has several advantages in use, it is a clean has less than emissions of CO2, and other greenhouses produce from burn Fossil fuel in the conventional power plant. Leading to significantly participate in reduced emissions of (CO_2) to climate, also cheap is as available in the region of plant use, safe and easy to use and easy to deliver the type of fuel among all energy sources. The optimally combined cycle power plants categorized by minimum specific yearly cost values. Recent Improvements on gas turbine have led to extensive use of combined power plant for electrical generation power and made it possible to reach a thermal efficiency of (55–60%) (S. Boonnasaa, 2004). The optimally combined cycle power plants characterized by minimum specific annual cost values (Çengel & Boles, 2015).

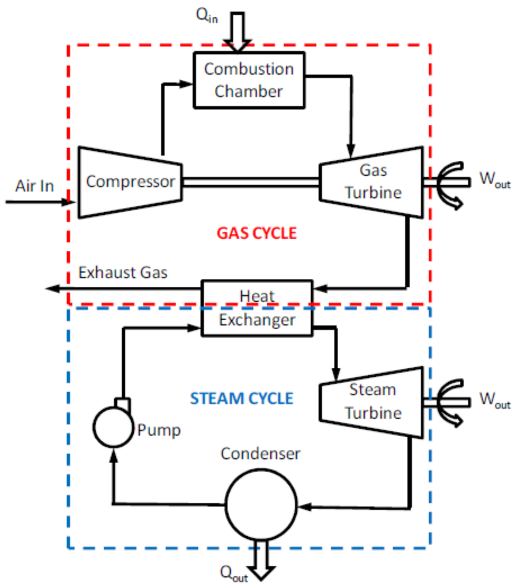

Figure 1.2: Thermodynamic layouts of combined cycle power plant (Çengel & Boles, 2008)

As shown in Figure 1.2, fuel (natural gas) is burned with air in the combustion chamber for the gas turbine. The energy release from the combustion operation makes the turbine is rotating. This rotation produces work used to turn the generator and produce electricity. The modern gas turbines have efficiency around (40%). (Çengel & Boles, 2008)

The exhaust gasses are hot of the gas turbine are used to create steam for the steam cycle, by using heat recovery steam generation (HRSG). This steam provides to get more work from a steam turbine. Also, the steam turbine will be rotating and produces work and using to generating addition power. Furthermore, if steam desired for other processes, some of the steam generated from the HRSG can be removed from the steam cycle (Nicola Palestra, 2008). The combined cycle power plants are typically artificial with standard components, which are combined to meet specific user needs (Naradasu, 2007). These plants can be operated by a variation of fuels, containing natural gas, fuel oils, as well as gasified coal.

1.2 PROBLEM STATEMENT

One of the major drawbacks of the combined cycle power plant (CCPP) operating in subtropical countries is the rapid performance drop when ambient air temperature increases (S. Boonnasaa, 2004). In the area where the Combined Cycle Power Plant considered for this study is located the ambient air temperature varies between (15℃) and (45℃) during the day and also varies along the year, which has also been recorded in the past data acquired from the power station. From the daily readings of the particular combined cycle power plant located subtropical country, it can be noticed that full load capacity drops during hot daytime with about (1-2 MW) out of the overall output achieved in morning and night hours (Guoqiang Zhang, 2014).

1.3 OBJECTIVES

The purposes of this study are summarized as follows:

- To develop an integrated thermodynamic model based on thermodynamic analysis for enhancing the performance of combined cycle power plant and to the cooling system.
- To investigate the impact of operating particular variable (ambient air temperature) on combined cycle power plant for improving the thermal efficiency and power output.
- To optimum the thermal efficiency different and other parameter involved in the performance of the combined cycle power plant to obtain the optimum performance based on thermodynamic analysis

1.4 METHODOLOGY

The primary object of this research is a focus on the investigation of the cooling system for the inlet air to the gas turbine of combined cycle power plant. As the first step, a literature survey was carried out to study the inlet cooling methods, advantages, disadvantages of specific methods, theoretical background of the inlet cooling and the combined cycle power plant operation. Analysis and discuss the relationship between an inlet air cooling system with combined cycle performance.

A combined cycle power plant located in subtropical was used for evaluating the performance with the changes in the ambient air temperature. Two approaches have been applied to study this phenomenon. Firstly, changes were calculated by actual data acquired by the operation history of the power plant. The required data needed for the analysis obtained from the data sheets of the power plant and the machine manuals.

These analyzed data given a determining of the patterns performance variations with air temperature. Secondly, the performance was analyzed using thermodynamic principles. Then the results of the two approaches are compared. In the next phase, energy calculations were performed to obtain the required level of the charge air cooling and to select a suitable capacity of an absorption chiller.

1.5 SCOPES

This research seeks to improve the overall performance of the combined cycle power plants by using a cooling system. The scope of the study is outlined as follows:

- The thermodynamic model is developed to estimate the performance of the combined cycle power plant for various ambient temperature ranges from 15 ºC to 45 ºC.
- The effect of one operation parameter (ambient temperature) on the performance of power plants.
- The energy analysis by using the first law of thermodynamics to measure the performance of the combined cycle power plant adopted, While, the fluid flow and aerodynamics and exergy analysis are out of the scope.

The study models are evaluated based on the actual data of real combined cycle power plants through a typical year in the subtropical region.

1.6 THESIS OUTLINE

The thesis is organized as follows:

Chapter 2: Introduce the effect of one operation parameter (ambient temperature) on the performance of combined cycle power plant. A review of the past work in cooling techniques has been covered.

Chapter 3: In this chapter, the thermal analysis CCPP performance of actual data and thermodynamic model were presented. Also, optimize the CCPP performance by using RBFNN optimization technical.

Chapter 4: This chapter describes the results of a CCPP performance actual data, model, with and without using the cooling system. Moreover, the optimization results with use RBFNN. Comparison graphs were implemented to compare the result of using the cooling system. The performance of Absorption chiller as a cooling system presented with the ambient temperature varying.

Chapter 5: This chapter summarizes and highlights the contributions of the thesis, followed by future directions of research.

CHAPTER TWO

LIT ERATURE REVIEW

2.1 INTRODUCTION

This chapter reviews a comprehensive knowledge of past research efforts of cooling inlet air to gas turbine of combined cycle power plant. Over the past periods, many studies conducted to improve the performance of combined cycle power plant. Some of these studies have focused on inlet air cooling systems of the gas turbine. However, it is still a small number of studies in this domain. Therefore, the current study focused on detailed review the past work of cooling system methods.

2.2 AMBIENT TEMPERATURE EFFECT

Is well recognized, that the performance of the gas turbine (GT) in combined cycle power plants depends largely on the ambient conditions especially, the decline in power production is the result of the higher air temperature. Inlet air temperature to the gas turbine is an effective factor in increasing the performance of the gas turbine (Brayton cycle) (Thamir K. Ibrahim, 2010). A decrease the temperature of inlet air can significantly increase the power output of gas turbines. However, this decline in the temperature of the inlet air increases the fuel consumption rate required to achieve the required operating temperature at the inlet of the gas turbine. (A. K. Tiwari, 2012)

The mass of the fuel consumption is derived based on the energy balances at the combustion and reheat chambers. The increasing in fuel consumption has a direct influence on the flow rate of exhaust gas, and the increased temperature of inlet air produce a high temperature of flue gases liberated from the gas turbine. That leads to lower pressure ratios with a rise in temperature air inlet designed to provide a gas turbine inlet temperature. (Gowtham Mohan, 2014)

The increase in the ambient air temperature leads to the falls the air density, hence at a high temperature of inlet air over (15°C). The mass flow of the air through the gas turbine has been reduced (Kakaras. E, 2004). As a sequel, the GT output power is lower, and the net power generated in the combined cycle thermal plant decreases despite the use of the maximum supplementary firing. Arrieta & Lora 2010 registered that with a gas temperature of (675°C) after the supplementary firing, the net electric power varies in the range from (640 to 540 MW) when the ambient temperature varies between (0°C) and (35°C).

Mohan 2014, in his quest review the performance of the Brayton cycle in the phrase of the electricity power generation and the mass of fuel consumption is shown in Figure 2.1. As previously, the temperature of the inlet air is the effective parameter on the Brayton cycle performance. Mohan, find the output power of the gas cycle reduces by (12%) in the months of summer. The maximum productivity of (34 MW) achieved during the winter months. Annual variations in the amount and temperatures of flue gases are shown in Figure 2.1 (Gowtham Mohan 2014).

During the summer months, the flue gases temperature maximizes, and the pressure ratio decreases at higher temperatures of the inlet air. The mass flow rate of exhaust gases liberated from the gas cycle reduced in summer due to the reduction of fuel consumption and rate of the inlet air (Gowtham Mohan 2014). Also, the power plant location plays a primary role in its performance. Because the temperature and humidity of the ambient air and other climatic factors. The atmospheric air which enters the compressor gets hotter after compression and goes to the combustion chamber(CC). While in the same year that when ambient temperature increase from (273°K) to (333°K), the total power output increase about (7%) for all configurations accept the regenerative gas turbine.

The overall thermal efficiency of the combined cycle which obtained the maximum value for regenerative gas turbine configuration about (62.8%) at ambient temperature (273 K). The minimum value of the overall thermal efficiency was about (53%) of the coolant gas turbine configuration in ambient temperature (333K) (Tiwari. A.K, 2012).

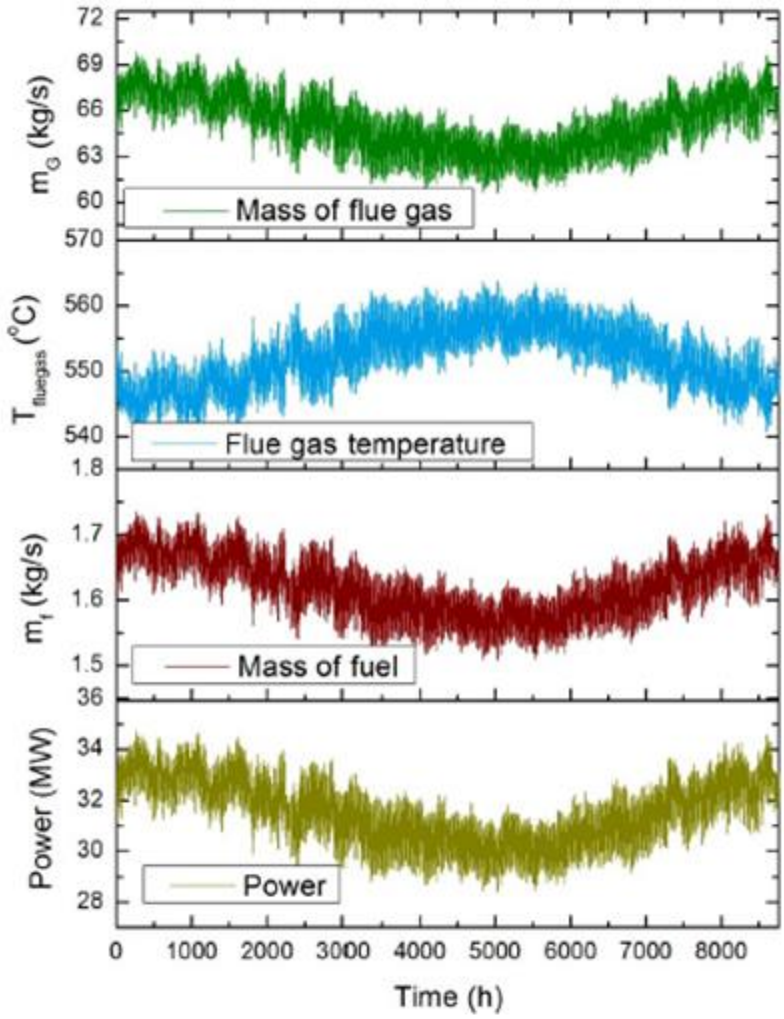

Figure 2.1: Annual variation in power production, intake, rate of fuel and exhaust gas parameters in the gas cycle (Gowtham Mohan, 2014)

2.3 LITERATURE REVIEW

BACKGROUND AND PAST WORK

The gas turbines design based on constant volumetric flow rate machine, move a given volume of air at a given shaft speed (Rahman. M.M, 2011). Because the required air for combustion is supplied directly from the environment, the weather conditions have significantly impacted on the performance of the gas turbines. So adoption of inlet air cooling systems appears an attractive choice in almost all combined cycle power plant configurations. Therefore, it necessitated to the development of standard criteria

CHAPTER ONE

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CHAPTER THREE

METHODOLOGY

3.1 INTRODUCTION

This chapter presents the explanation of the adopted methods in this study to enhance the performance of the combined cycle power plant. The thermal analysis models based on the first law of thermodynamic of combined cycle power plant presented, and that includes the core components of the plant. The components are the gas turbine, steam turbine and the heat recovery steam generator (HRSG). Also, the single-effect absorption chiller LiBr-water cooling system, which used to cool inlet air of the gas turbine. All these thermodynamic models are based on the first law of thermodynamics as we mentioned above. The CCPP thermodynamic model developed for evaluating the performance of the combined cycle. Moreover, its modifications (performance enhancing strategy) for one parameter which is the compressor inlet air temperature cooling system. The model of single effect absorption chiller developed for evaluating the coefficient of performance (COP).

3.2 POWER PLANT DESCRIPTION

The combined cycle power plant which was studied as we mentioned in chapter one located in the subtropical region in a middle east. The power plant consists of three gas turbines, three heat recovery steam generator, and one Steam turbine. The gas turbines work with natural gas and the rated power of (177.95 MW) for each one, and the total power output all gas turbines are (533.85 MW). The steam turbine produced power (343.60 MW), and the overall power output of the combined cycle power plant is (877.45 MW).

3.3 STRATEGY OF WORK FRAME

The flowchart of the strategy framework for performance enhancing strategy combined cycle power plant (CCPP) for the present study described in Figure 3.1. It shows the thermal analysis for the model and actual data of CCPP. According to this framework, the results are clarified in a logical manner. The outcomes of this framework strategy summarized in the conclusions and recommendations of future studies.

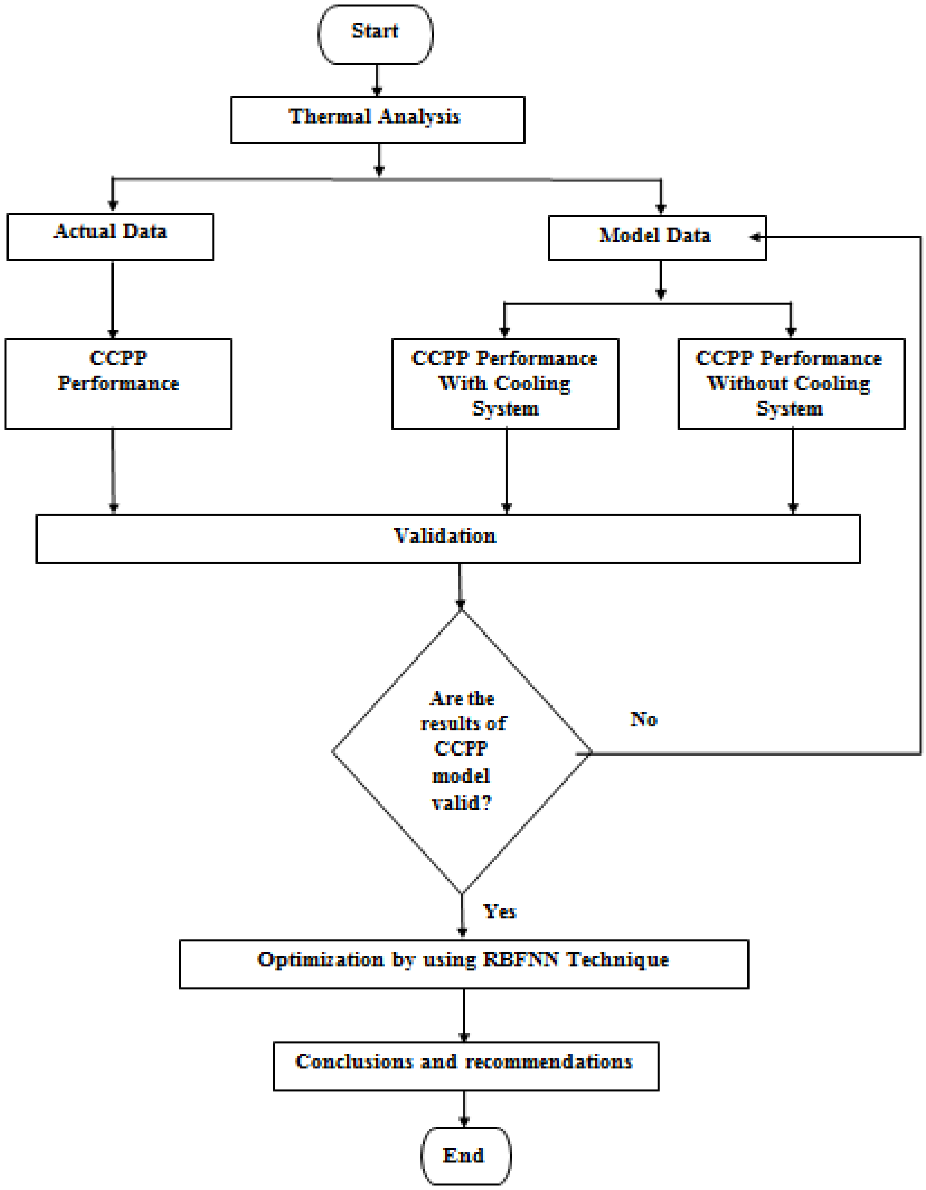

Figure 3.1: Strategy of the work frame for the current research methodology

3.4 THERMODYNAMIC APPROACH ON THE COMBINED CYCLE

The thermodynamic analysis of CCPP in this chapter is a brief outline of the generalized the output power, efficiency, and its characteristics. The air-standard Brayton cycle and the Rankine cycle are assumed for the analysis of the thermodynamic processes. That Brayton cycle consists of a gas turbine, and the Rankine cycle includes a steam turbine and a heat recovery steam generator (Adrian Tica, 2012).

3.4.1 IDEAL BRAYTON CYCLE

The Brayton cycle is a thermodynamic cycle that defines the working of a constant pressure of heat engine. Although the Brayton cycle is commonly run as an open system and indeed must be run as such if internal combustion used (Alok Ku, 2014). The gas turbine in combined cycles operates using the thermodynamic principles of the Brayton cycle. The ideal cycle of the Brayton cycle operates on four internally reversible processes. Figure 3.2 shows a graphical representation of the four thermodynamic states of the Brayton cycle on (P – V) and (T – S) diagrams (Matthew, 2011).

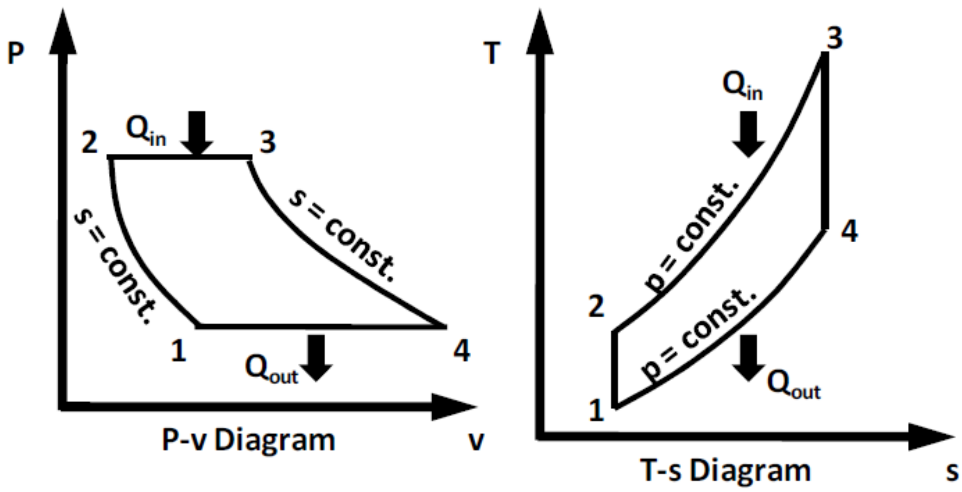

Figure 3.2: Thermodynamic states of the Brayton cycle (Brayton Energy, n.d.).