SUDAN UNIVERSITY
OF SCIENCE AND TECHNOLOGY
COLLEGE OF GRADUATE STUDIES

Energy and Exergy Analysis for Garri(4) Thermal Power Plant

تحليل الطاقة و الاكسيرجي لمحطة قري(4) للطاقة الحرارية

A Thesis Submitted in Partial Fulfillment of the Degree of M.Sc. in Mechanical Engineering (POWER)

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DEDICATION

To my ***father*** *who gives me direction to the sky*

To my ***mother*** *who gives me lovely life*

To my ***brothers*** *and* ***sisters*** *who give me support*

To my ***relatives*** *and* ***friends*** *who give me support*

And last but not least I would like to dedicate this work to my friends ***Mr : (M.siddig abuelgasim, Osman bashir)****, and all friends and colleagues who helped direct or indirect to complete this research .*

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ABSTRACT

In recent years the entire world is awarring about energy resources limitation, specifically sudan country confronts critical crises in fossil fuel resources and yet more of electricity energy producing from fired thermal power plants. one from these plants Garri(4) steam turbine producing about 110 MW. exergy analysis in the light second law of thermodynamics is powerful tools to innvistigate from optimization of engineering devices. Exergy analysis has been carried out analytically for Garri(4) to evaluate exrgetic efficiency and exergy destruction of each part ; exergy balance and entropy generation calculated to achieve it.

The results showed that combustion chambers are the main source of exergy destruction due to high irreversibilities representing (80.4%) from total exergy destruction, turbine (18.24%) , condenser (1.1%), and the heaters about (1%). The results also showed that thermal and exergetic efficiencies for entire plant (31%,27%) respectively.

مستخلص البحث

في السنوات الأخيرة زاد قلق العالم بمحدودية مصادر الطاقة والسودان كما نعلم يواجه أزمة حادة في مصادر الوقود الاحفوري ومع ذلك معظم الطاقة الكهربائية يتم إنتاجها من محطات توليد حراري واحدة من هذه المحطات محطة قري (4) التي تعمل بالتوربين البخاري وتنتج حوالي 110 ميقاواط. تحليل الاكسيرجي على ضوء القانون الثاني للديناميكا الحرارية يعتبر أداة فعالة جداً للتحقق من كفاءة المنظومة الهندسية. تم إجراء تحليل الانيرجي والاكسيرجي لمحطة قري (4) لحساب كفاءة الاكسيرجي وحساب الاكسيرجي المتبدد في كل وحدة من وحدات المحطة على حدة، تم استخدام موازنة الاكسيرجي وحساب الانتروبي المتولد لانجاز الدراسة. أظهرت الدراسة أن غرف الاحتراق هي المصدر الرئيسي في تبديد الاكسيرجي وتمثل حوالي(80.4%)، التوربين (18.24%)، المكثف (1.1%)، السخانات (1%). كما أظهرت النتائج أن المحطة بظروف التشغيل المدروسة تعمل بكفاءة حرارية (31%) وكفاءة اكسيرجي (27%).

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NOMENCLATURE

Symbols:
HPH = High pressure heater
LPH = Low pressure heater
CRT = Condensate return tank
ex = Specific exergy.
ex_{ph} = Physical exergy
ex_{ch}= Chemical exergy
c_p = Specific heat.
T = Absolute temperature (k).
T_o= Ambient temperature (k).
EX = Exergy rate (MW).
EX_d = Exergy destruction rate (MW).
EX_{td} = Total exergy destruction.
h = Specific enthalpy (Kj/Kg)
s = specific entropy (kj/kg).
S_{gen} = Entropy generation rate (MW/k).
η_{th} = Thermal efficiency.
$\eta_{th,rev}$ = Carnot (maximum available) efficiency.
η_{ex} = Exergetic (second law) efficiency.

Subscript and superscript:
f= fuel.
w =water.
p = pressure.
POW= power.
i= in.
e = exit.
0= ambient condition.
el = element

CHAPTER ONE

INTRODUCTION

1.1 Introduction

Power generation industry plays a key role in the economic growth of a country. Therefore, the demand of energy is increasing day by day. Rapid utilization of fossil fuel resources to meet the increasing energy demand is not only causing these resources to diminish faster but also causing the environmental degradation [1].

Figure 1.1 shows the world energy consumption by fuel [2].From this Figure, we readily observe that the world's three main sources of energy are coal, natural gas and oil; each of which depends upon combustion. In the foreseeable future, these energy sources are expected to continue their domination.

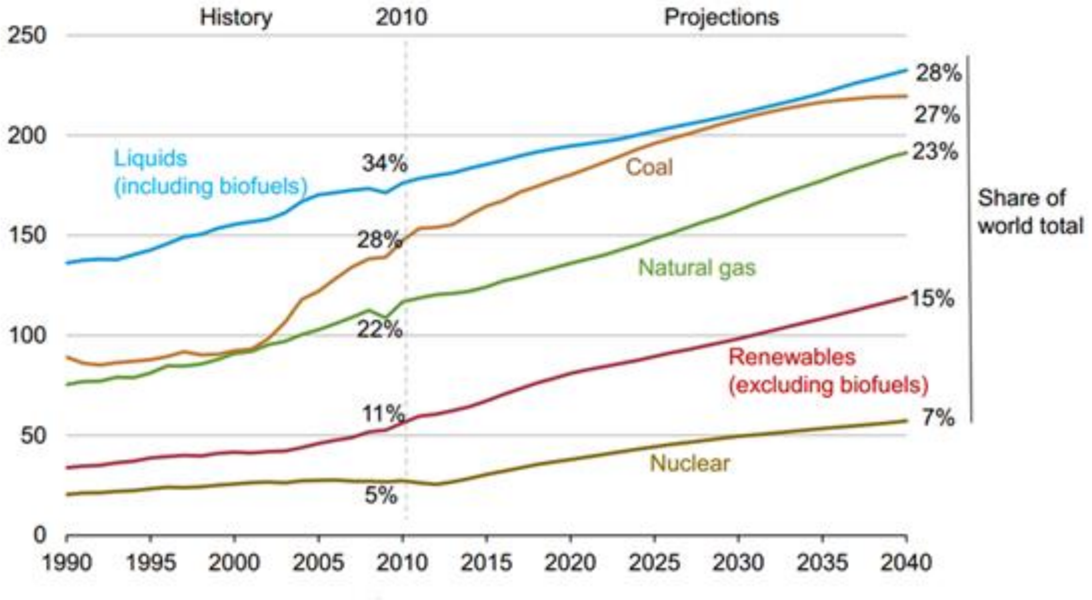


Figure 1.1: World energy consumption by fuel quadrillion Btu

Recently, the use of energy and other resources in the industrial world has reached levels never observed before. This leads to a decreasing supply of natural resources and an increasing amount of damage to and pollution of the natural environment.

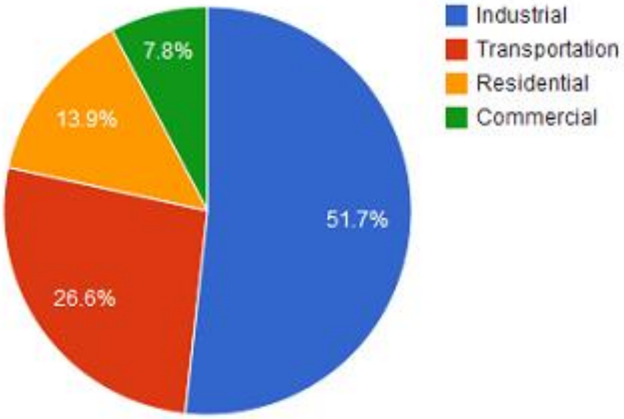


Figure 1.2: World energy consumption by sector[2].

At the same time, energy resource conversion networks have become more complicated. Technical improvements are often focused towards less important resource conversions, which do not have significant potential to improve resource use. By describing the use of energy resources in society in terms of exergy, important knowledge and understanding can be gained, and areas identified where large improvements could be obtained by applying efficient technology, in the sense of more efficient energyresource conversions.

Nearly 45% of global electricity generation is derived from coal while natural gas and nuclear energy makes up about 20% and 15%, respectively of the world's electricity generation[3].

Due to the high prices of energy and the decreasing fossil fuel recourses, the optimum application of energy and the energy consumption management methods are very important. This, in fact, requires accurate thermodynamic analysis of thermal systems for design and optimization purposes. In this regard, there are two essential tools available, such as energy analysis (referring to the first law of thermodynamic analysis) and exergy analysis (referring to the second law of thermodynamic analysis).

The first law of thermodynamics states that when looking at the system and surroundings together, the total amount of energy will remain constant. The first law treats the different forms of energy as equivalent and does not distinguish the difference in quality between, among others, mechanical and thermal energy. Exergy analysis based on the first and second thermodynamic laws is a significant tool to analyze the energy systems. It also reveals the inefficient thermodynamic processes.

Recently, exergy analysis has become a key issue in providing a better understanding of the processes, to quantify sources of inefficiency, and to distinguish quality of energy consumption. It is well known that the exergy can be used to determine the location, type, and true magnitude of exergy loss (or destruction). Thus, it can play an important role in developing strategies and in providing guidelines for more effective use of energy in the existing power plants. Moreover, another important issue for improving the existing system is the origin of the exergy loss. Hence, a clear picture, instead of only the magnitude of exergy loss in each section, is required. Therefore, the exergy analysis has been widely used for the evaluation of the thermal power plants[4].

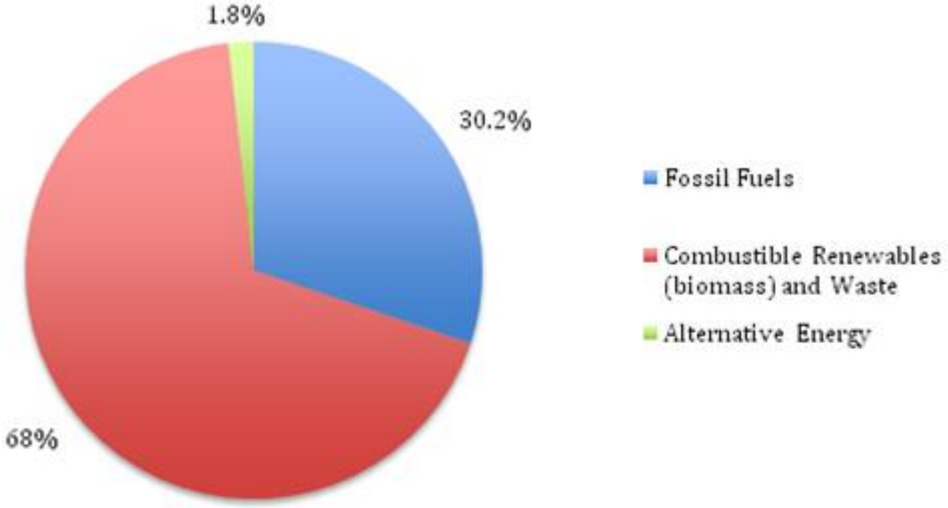


Figure 1.3: Sudan's energy consumption

The thermal power plant are widely used in Sudan grid network, Garri "4" consider one from these plants producing about 110 MW in design condition this study aimed to estimate exergy destruction due to processes individually and calculate exergy efficiency to know what is process less efficient and made compare with other literature review to satisfy whether plant under study operated with reasonable accuracy or not for either process.

1.2 Problem statement

Current research and development in the field of combustion engines technology was focused to improvements combustion engines performance. There are many methods and approaches to solutions these problems, one of which is energy and Exergy analysis. Analysis in the light of second law of thermodynamics require to evaluate exergy destruction of each part; to determine the parts has major contribute in exergy destruction.

1.3 Objective study

The objective of this study is to evaluate the energy and exergy (second law) analysis of the performance of Garri (4) an existing 110 MW (fuel-fired) electrical steam cycle power plant to identify the potential for improvement.

1.4 Scope

Energy and exergy destruction to main equipments (steam turbine, boiler, condenser , boiler feed pump, heaters)

1.5 Significance of Research

The significance of this study as follows:

1. Facilitate the achievement of better and more efficient combustion engine processes for all concerned industries.
2. This study will assist industrial energy conservation by offering an improved approach to thermal efficiency.

CHAPTER TWO

LITERATURE REVIEW

2.1 Preface

Many current energy policies promote research to enhance the utilization of renewable energy sources, in large part to help mitigate environmental problems and improve the national energy security of countries dependent on the use of imported fossil fuels. Others use nuclear power[5].

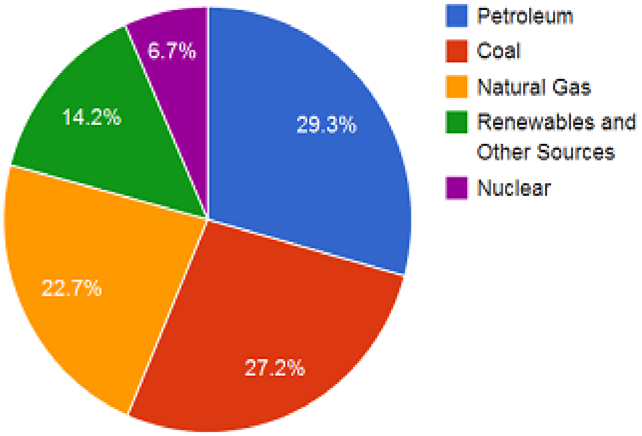


Figure 2.1: World energy mix[2]

but there is an increasing use of cleaner renewable sources such as solar, wind, wave and hydroelectric[6-8] and we know electricity of the world produced from a lot of sources.

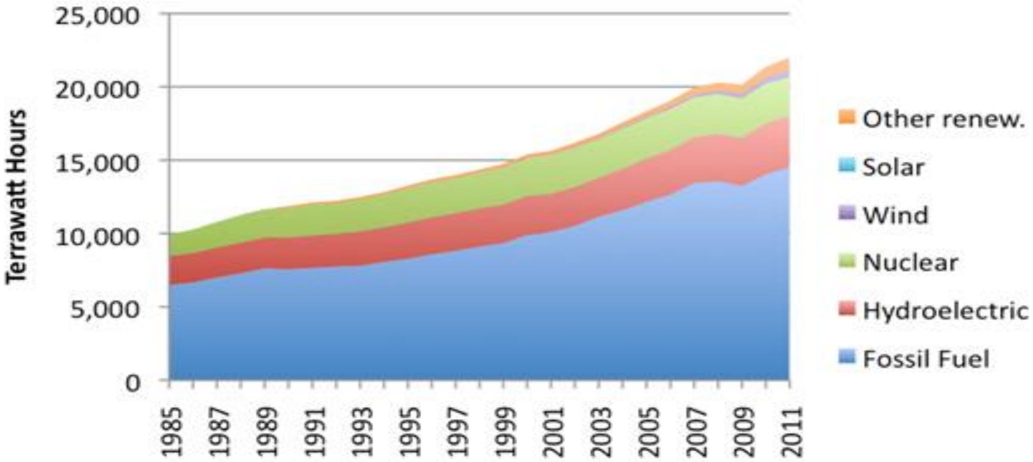


Figure 2.2: World electricity by source[2]

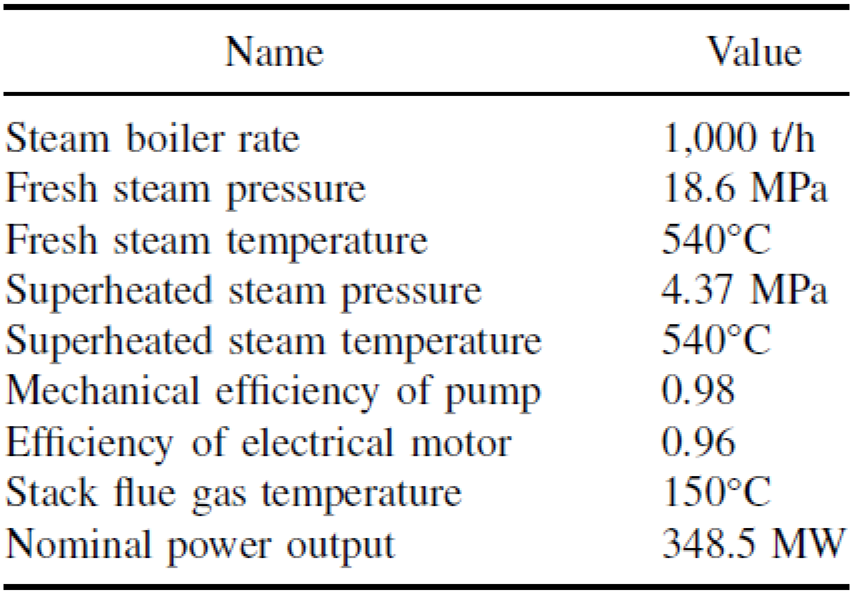
A turbo machinery fired thermal power plants are producing most electric energy in the world; this type of plants operate on a deferent cycle and modes as a follow. The Brayton cycle was first proposed by George Brayton for use in the reciprocating oil-burning engine that he developed around 1870[9].Today, it is used for gas turbines only where both the compression and expansion processes take place in rotating machinery. Gas turbines usually operate on an open cycle, Fresh air at ambient conditions is drawn into the compressor, where its temperature and pressure are raised. The high pressure air proceeds into the combustion chamber, where the fuel is burned at constant pressure. The resulting high-temperature gases then enter the turbine, where they expand to the atmospheric pressure while producing power. The exhaust gases leaving the turbine are thrown out (not recalculated), the cycle to be classified as an open cycle. The open gas-turbine cycle described above can be modeled as a closed cycle, by utilizing the air-standard assumptions. Here the compression and expansion processes remain the same, but the combustion process is replaced by a constant-pressure heat-addition process from an external source, and the exhaust process is replaced by a constant pressure heat-rejection process to the ambient air. The processes taking place in power-generating systems are sufficiently complicated that idealizations are required to develop thermodynamic models. Such modeling is an important initial step in engineering design. They also provide relatively simple settings in which to discuss the functions and benefits of features intended to improve overall performance. The vast majority of electrical generating plants are variations of vapor power plants in which water is the working fluid. The basic components of a simplified fossil-fuel vapor power plant. To facilitate thermodynamic analysis, the overall plant can be broken down into the four major subsystems[10].The continued quest for higher thermal efficiencies has resulted in rather innovative modifications to conventional power plants. The binary vapor cycle discussed later is one such modification. A more popular modification involves a gas power cycle topping a vapor power cycle, which is called the combined cycle power plant, or just the combined cycle. The combine cycle of greatest interest is the gas-turbine (Brayton) cycle topping a steam turbine (Rankine) cycle, which has a higher thermal efficiency than either of the cycles executed individually Gas-turbine cycles typically operate at considerably higher temperature than steam cycle?

2.2 Plant Description of Kostolac B

The coal-fired power plant “Kostolac B” was been built in 1990/1991. It consists of two identical units. The operation conditions of the steam power plant are listed in Table 3. The plant’s primary fuel is lignite from the nearby mine, Drmno. Lower heating values of this fuel are mainly above 6,845 kJ/kg.

Preheating of the condensed steam is done in the low pressure preheating part of the plant, which includes four low pressure heaters (LPH4, LPH5, LPH6, LPH7). Heating up the boiler (SB) feed water to the final stage at the input of the boiler is done by two high pressure regenerative heaters (HPH1, HPH2).

Table (2-1) The operation condition of the steam power plant.



Name	Value
Steam boiler rate	1,000 t/h
Fresh steam pressure	18.6 MPa
Fresh steam temperature	540°C
Superheated steam pressure	4.37 MPa
Superheated steam temperature	540°C
Mechanical efficiency of pump	0.98
Efficiency of electrical motor	0.96
Stack flue gas temperature	150°C
Nominal power output	348.5 MW

These devices are supplied with heating steam from the extraction ports (Ep1, Ep2,). Removing the non-condensable gases from the steam cycle is realized by the deaerator (DA3). Exhaust steam from a low pressure turbine is completely condensed in the surface condenser (CN). For cooling its condenser, the “Kostolac B” power plant uses cooling water from the

Danube. The temperature of this cooling water varies from around 6ıC in winter up to 26ıC in summer. At this moment, the cooling water flow rate cannot be controlled. Turbine 18 K 348 of this plant is four-cylindrical, reaction-axial flow with overheating between stages. It consists of a high pressure turbine (HPT), medium pressure turbine (MPT), and two low pressure turbines (LPT).

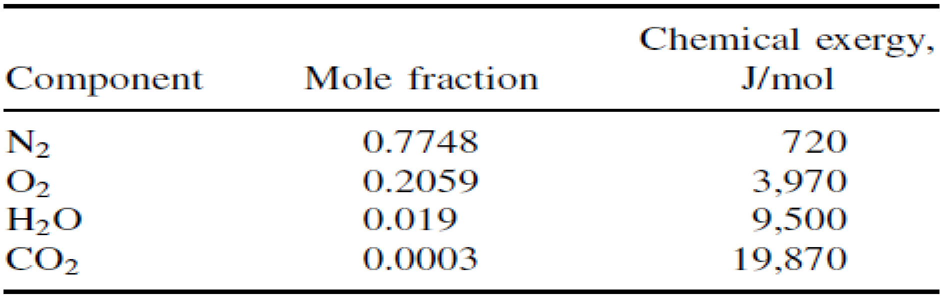
2.2.1 Reference Environment

The reference environment state is irrelevant for calculating a change in a thermodynamic property (first law analysis). However, exergy analysis cannot be performed without defining the environment and it varies from region to region and from one study to another. In the present study, the temperature and pressure of the environment are taken as 298.15 K and 1.013 bars.

2.2.2 Fuel Used

A short calculation of flue gas exergy will be provided based upon certain assumptions. Fuel used in calculation is a hard coal with standard composition (Table 5). Combustion is complete with 70% of air excess, and outgoing flue gas temperature is 150C.

Table (2-2) Mole fractionsand chemical exergy of the reference components in atmospheric air.

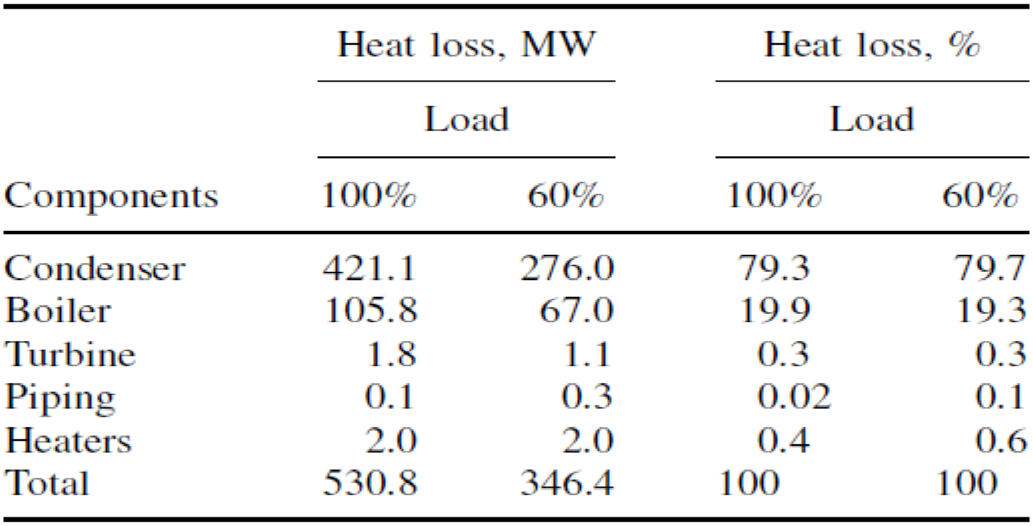


Component	Mole fraction	Chemical exergy, J/mol
N_2	0.7748	720
O_2	0.2059	3,970
H_2O	0.019	9,500
CO_2	0.0003	19,870

Table (2-3) Chemical composition (by mass) of coal.

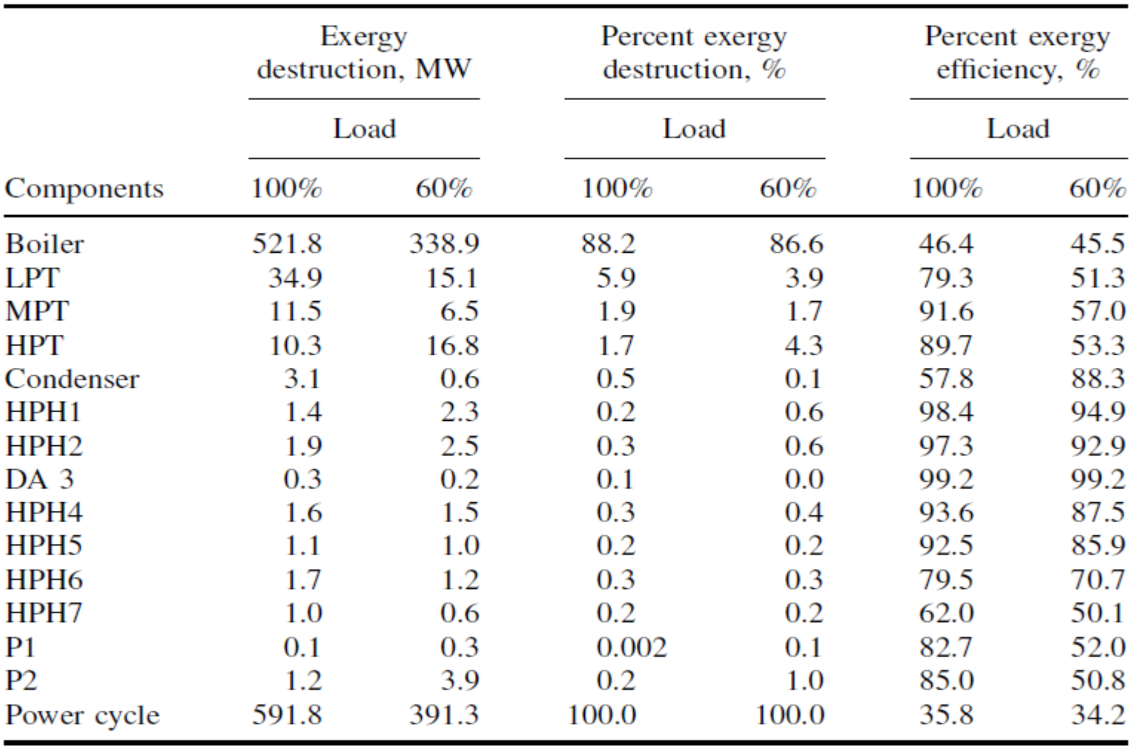
C, %	H, %	S, %	O, %	N, %	A, %	H_2O, %	LHV, J/kg
20.38	1.83	0.65	7.98	0.6	23.56	45	6,845

Table (2-4) Heat loss ratio of the steam power plant components



	Heat loss, MW		Heat loss, %	
	Load		Load	
Components	100%	60%	100%	60%
Condenser	421.1	276.0	79.3	79.7
Boiler	105.8	67.0	19.9	19.3
Turbine	1.8	1.1	0.3	0.3
Piping	0.1	0.3	0.02	0.1
Heaters	2.0	2.0	0.4	0.6
Total	530.8	346.4	100	100

Table (2-5) Exergy destruction and exergy efficiency of the steam power plant components.



	Exergy destruction, MW		Percent exergy destruction, %		Percent exergy efficiency, %	
	Load		Load		Load	
Components	100%	60%	100%	60%	100%	60%
Boiler	521.8	338.9	88.2	86.6	46.4	45.5
LPT	34.9	15.1	5.9	3.9	79.3	51.3
MPT	11.5	6.5	1.9	1.7	91.6	57.0
HPT	10.3	16.8	1.7	4.3	89.7	53.3
Condenser	3.1	0.6	0.5	0.1	57.8	88.3
HPH1	1.4	2.3	0.2	0.6	98.4	94.9
HPH2	1.9	2.5	0.3	0.6	97.3	92.9
DA 3	0.3	0.2	0.1	0.0	99.2	99.2
HPH4	1.6	1.5	0.3	0.4	93.6	87.5
HPH5	1.1	1.0	0.2	0.2	92.5	85.9
HPH6	1.7	1.2	0.3	0.3	79.5	70.7
HPH7	1.0	0.6	0.2	0.2	62.0	50.1
P1	0.1	0.3	0.002	0.1	82.7	52.0
P2	1.2	3.9	0.2	1.0	85.0	50.8
Power cycle	591.8	391.3	100.0	100.0	35.8	34.2

For the overall plant, the energy efficiency, defined as the ratio of net electrical energy output to coal energy input, was found to be 37.5%, and the corresponding exergy efficiency was found to be 35.77% for 100% of full load. When load 60% of full load energy efficiency of plant is 37.4%, and the exergy efficiency is 34.2%.

Jordan’s energy market is one of the country’s fastest developing sectors. Annual demand for electricity has increased by more than 9% during recent years, and installed capacity and annual generation figures have reached in 2006 approximately 9000 GW h[11].Central Electricity Generating Company (CEGCO) is the sole power generating company in the country using heavy fuel oil, diesel, gas, and renewable resources. The power plants are distributed over most of the Jordanian cities, all of which are transmitting power through overhead lines of 132 and 400 kV. Analysis of power generation systems are of scientific interest and also essential for the efficient utilization of energy resources. The most commonly-used method for analysis of an energy-conversion process is the first law of thermodynamics. However, there is increasing interest in the combined utilization of the first and second laws of thermodynamics, using such concepts as exergy and exergy destruction in order to evaluate the efficiency with which the available energy is consumed. Exergetic analysis provides the tool for a clear distinction between energy losses to the environment and internal irreversibilities in the process[12]. Exergy analysis is a methodology for the evaluation of the performance of devices and processes, and involves examining the exergy at different points in a series of energy-conversion steps. With this information, efficiencies can be evaluated, and the process steps having the largest losses (i.e., the greatest margin for improvement) can be identified[13]. For these reasons, the modern approach to process analysis uses the exergy analysis, which provides a more realistic view of the process and a useful tool for engineering evaluation[14]. As a matter of fact, many researchers[15-18]. have recommended that exergy analysis be used to aid decision making regarding the allocation of resources (capital, research and development effort, optimization, life cycle analysis, materials, etc.) in place of or in addition to energy analysis[19].

Exergy analysis has become a key aspect in providing a better understanding of the process, to quantify sources of inefficiency, and to distinguish quality of energy used[20].Some researchers dedicated their studies to component exergy analysis and efficiency improvement[21, 22]; others focused on systems design and analysis[23-28]. The objective of this work is to analyze Al-Hussein power plant from an energy and exergy perspective. Sites of primary energy loss and exergy destruction will be determined. The effect of varying the reference environment state (dead state) on the exergy analysis will also be investigated.

2.3 Plant description of Alhussein

The power plant has a total installed power capacity of 396 MW. It is located 560 m above sea level in the city of Zarqa, at north east of Jordan 30 km of Amman. It started to produce power in the middle seventies. The power house consists of seven steam turbines units (3 33 + 4 66) MW and two gas turbines (1 14 + 1 19) MW at 100% load. The power plant uses heavy fuel oil, which is obtained from a nearby oil refinery. The annual fuel consumption in the year 2006 is 504,030 tons. Properties for the heavy fuel oil obtained in the month of April, 2007 are shown in Table 1.

Table (2-6) Properties of heavy fuel oil used in Al-Hussein power plant for April2007.

Property	Value
Density at 15 C	0.9705 g/mL
Total sulfur	3.76 wt%
Flash point	117 C
Kinematic viscosity @ 100 C	35.52 cSt
Pour point	+7 C
Ash content	0.036 wt%
Water and sediment	0.14 V%
Gross calorific value	42943.81 kJ/kg
Net calorific value	40504.58 kJ/kg

The schematic diagram of one 66 MW unit is shown. This unit employs regenerative feed water heating system. Feed water heating is carried out in two stages of high pressure heaters (HPH1,HPH2) and two stages of low pressure heaters (LPH4,LPH5) along with one deaerating heat exchanger. Steam is superheated to 793 K and 9.12 MPa in the steam generator and fed to the turbine. The turbine exhaust stream is sent to an air-cooled condenser and the condensate to the condensate return tank (CRT).

Table(2- 7) Operating conditions of the power plant.

Operating condition	Value
Mass flow rate of fuel	5.0 kg/s
Inlet gas volumetric flow rate to burners	188,790 N m3/h
Stack gas temperature	411.15 K
Feed water inlet temperature to boiler	494.15 K
Steam flow rater	275 ton/h
Steam temperature	793.15 K
Steam pressure	9.12 MPa
Power output	56 MW
Power input to FDC/fan	88 kW
Number of fans	18
Mass flow rate of cooling air	23,900 ton/h
Combined pump/motor efficiency	0.95

2.4 Exergy analysis

Exergy is composed of two important parts. The first one is the physical exergy and the second one is the chemical exergy. The kinetic and potential parts of exergy are negligible. Exergy is defined as the maximum theoretical useful work that can be obtained as a system interacts with an equilibrium state. The chemical exergy is associated with the departure of the chemical composition of a system from its chemical equilibrium. The chemical exergy is an important part of exergy in combustion process[27].

2.4.1 Exergy formulation

A general exergy balance equation, applicable to any component of a thermal system may be formulated by utilizing the first and second laws of thermodynamics. The thermo-mechanical (physical) exergy stream may be decomposed into its thermal and mechanical components. The balance gives[29]:

$$ex = ex_{ph} + ex_{ch} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-1)}$$

Physical exergy is defined as the follow[28]:

$$\mathrm{e}x_{\mathrm{ph}} = \mathrm{e}x_{\mathrm{T}} + \mathrm{e}x_{\mathrm{p}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-2)}$$

$$\mathrm{e}x_{\mathrm{T}} = \mathrm{c_p}\left[(\mathrm{T}-\mathrm{T_0}) - \mathrm{T_0}\ln\left({}^{\mathrm{T}}/_{\mathrm{T_0}}\right)\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-3)}$$

$$\mathrm{e}x_{\mathrm{P}} = \mathrm{RT_0}\ln(\mathrm{T}/\mathrm{T_0}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-4)}$$

Subs (3-2), (3-3) in (3-1) give

$$\mathrm{e}x_{\mathrm{ph}} = (\mathrm{h}-\mathrm{h_0}) - \mathrm{T_0}(\mathrm{s}-\mathrm{s_0}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-5)}$$

If one applies the first and second laws of thermodynamics, one can find the formula for exergy balance as[27,29]:

$$\mathrm{EX_Q} + \textstyle\sum_{\mathrm{i}} \mathrm{m_i}\mathrm{e}x_{\mathrm{i}} = \sum_{\mathrm{e}} \mathrm{m_e}\mathrm{e}x_{\mathrm{e}} + \mathrm{EX_P} + \mathrm{EX_d} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(2-6)}$$

$$EX_Q = \left(1 - {}^{T_0}/_{T_i}\right)Q_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-7)}$$

$$\mathrm{EX_P} = \mathrm{P} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-8)}$$

The chemical exergy for gas mixtures is defined as follows[30] :

$$\mathrm{ex_{ch}^{mix}} = \left[\textstyle\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{x_i}\mathrm{ex_{ch_i}} + \mathrm{RT_0}\sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{x_i}\ln\mathrm{x_i}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-9)}$$

For the evaluation of the fuel exergy, the (2-9) formula cannot be used. Thus, the corresponding ratio of simplified exergy is defined as the following[27,29] :

$\xi = \mathrm{e}x_{\mathrm{f}}/\mathrm{LHV}_{\mathrm{f}}$ …………………………….………............ (2-10)

The ratio of chemical exergy to $\mathrm{LHV}_{\mathrm{f}}$ is usually close to unity. In general fuel with chemical formula C_xH_y.

For gaseous fuels:

$\xi = 1.033 + 0.0169\,{}^{\mathrm{y}}/_{\mathrm{x}} - {}^{0.0689}/_{\mathrm{x}}$ ………………………...…. (2-11)

For liquid fuels[15]:

$\xi = 1.0422 + 0.011925\,{}^{\mathrm{y}}/_{\mathrm{x}} - {}^{0.042}/_{\mathrm{x}}$ ……………………….……. (2-12)

To find exergy destruction; exergy balance from equation (2-6) can be used and also entropy generation concept applicable to evaluate it if entropy generation can be calculated.

$\mathrm{EX}_{\mathrm{d}} = \mathrm{T}_0\mathrm{S}_{\mathrm{gen}}$ ……………………….…….…...… (2-13)

2.4.2 Efficiency laws

Efficiency is the (often measurable) ability to avoid wasting materials, energy, efforts, money, and time in doing something or in producing a desired result. In a more general sense, it is the ability to do things well, successfully, and without waste. In more mathematical or scientific terms, it is a measure of the extent to which input is well used for an intended task or function (output). It often specifically comprises the capability of a specific application of effort to produce a specific outcome with a minimum amount or quantity of waste, expense, or unnecessary effort. Specifically this text present most efficiencies uses in power plant analysis.

2.4.2.1 Thermal efficiency

The fraction of the heat input that is converted to network output is a measure of the performance of a heat engine and is called the *thermal efficiency* (η_{th}). For heat engines, the desired output is the net

Work output, and the required input is the amount of heat supplied to the working fluid. Then the thermal efficiency of a heat engine can be expressed as:

$$\eta_{th} = \frac{P_{net,out}}{Q_{in}} \quad \text{...} \quad (2\text{-}14)$$

Since ($P_{net,out} = Q_{in} - Q_{out}$) It can also be expressed as:

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} \quad \text{…………………………………………….} \quad (2\text{-}15)$$

2.3.2.2 Carnot efficiency

The hypothetical heat engine that operates on the reversible manner cycle is called the Carnot heat engine. The thermal efficiency of any heat engine, reversible or irreversible, is given by equation (2-15). Where $\mathrm{Q_{in}}$ heat is rate transferred to the heat engine from a high temperature reservoir at T_H, and $\mathrm{Q_{out}}$ is rate heat rejected to a low temperature reservoir at $\mathrm{T_L}$. For reversible heat engines, the heat transfer ratio in the above relation can be replaced by the ratio of the absolute temperatures of the two reservoirs, as given by equation (2-16). Then the efficiency of a Carnot engine, or any reversible heat engine, becomes

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H} \quad \text{……………………………………...…………} \quad (2\text{-}16)$$

2.4.2.3 Exergetic (second law) efficiency

In previous we defined the *thermal efficiency* for devices as a measure of their performance. They are defined on the basis of the first law only, and they are sometimes referred to as the *first law efficiency.* The first law efficiency, however, makes no reference to the best possible performance, and thus it may be misleading; because it is not refer to maximum efficiency (Carnot efficiency) can be achieved**.**If reversible device, these can be treated by calculate ratio of actual thermal efficiency to the maximum possible (Carnot) efficiency under same condition equation (2-17) (For heat engine):

$$\eta_{ex} = \frac{\eta_{th}}{\eta_{th,rev}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-17)}$$

Subs (2-15), (2-16) in (2-17) exergy efficiency can be written as

$$\eta_{ex} = \frac{P_u}{P_{rev}} \quad \text{(Power–producing devices)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-18)}$$

$$\eta_{ex} = \frac{P_{rev}}{P_u} \quad \text{(Power –consuming devices)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-19)}$$

Exergy efficiency general formula (2-20) or (2-21):

$$\eta_{ex} = \frac{exergy\ recovered}{exergy\ supplied} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-20)}$$

$$\eta_{ex} = 1 - \frac{exergy\ destruction}{exergy\ supplied} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2-21)}$$

2.5 Exergy analyzed for thermal power plants

Energy and Exergy Analysis of a 348.5 MW Kostolac steam power plant in Serbia country is presented. The results show that energy losses have mainly occurred in the condenser where 421 MW is lost to the environment while only 105.78 MW has been lost from the boiler. Nevertheless, the irreversibility rate of the boiler is higher than the irreversibility rates of the other components. The percentage ratio of the exergy destruction to the total exergy destruction was found to be maximum in the boiler system (88.2%) followed by the turbines (9.5%), and then the forced draft fan condenser (0.5%). In addition, the calculated thermal efficiency based on the lower heating value of fuel was 39% while the exergy efficiency of the power cycle was 35.77%[28].

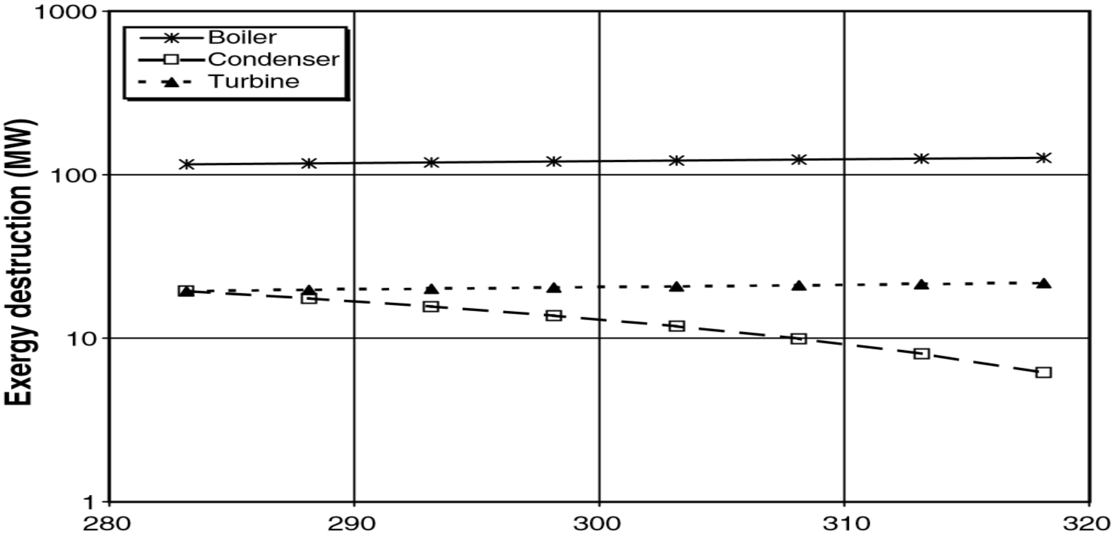
Energy and exergy analysis of Al-Hussein steam power plant in Jordan presented. The percentage ratio of the exergy Energy losses mainly occurred in the condenser where 134MW is lost to the environment while only 13 MW was lost from the boiler system. The percentage ratio of the exergy destruction to the total exergy destruction was found to be maximum in the boiler system (77%) followed by the turbine (13%), and then the forced draft fan condenser (9%). In addition, the calculated thermal efficiency based on the lower heating value of fuel was 26% while the exergy efficiency of the power cycle was 25%. For a moderate change in the reference environment state temperature, no drastic change was noticed in the performance of major components and the main conclusion remained the same; the boiler is the major source of irreversibilities in the power plant. Chemical reaction is the most significant source of exergy destruction in a boiler system which can be reduced by preheating the combustion air and reducing the air–fuel ratio[11]. Exergy is a measure of the maximum capacity of a system to perform useful work as it proceeds to a specified final state in equilibrium with its surroundings. Exergy is generally not conserved as energy but destructed in the system. Exergy destruction is the measure of irreversibility that is the source of performance loss. Therefore, an exergy analysis assessing the magnitude of exergy destruction identifies the location, the magnitude and the source of thermodynamic inefficiencies in a thermal system.

Table(2-8) Energy balance of the power plant components and percent ratio to fuel energy input.

Component	Heat loss (kW)	Percent ratio
Condenser	133,597	65.97
Net power	53,321	26.33
Boiler	12,632	6.24
Piping	1665	0.82
Heaters	856	0.42
Turbine	452	0.22
Total	202,523	100

Table (2-9) Exergy destruction and exergy efficiency of the power plant components when To = 298.15 K, Po = 101.3 kPa

	Exergy destruction (MW)	Percent exergy destruction	Percent exergy efficiency
Boiler	120.540	76.75	43.8
Turbine	20.407	12.99	73.5
Condenser	13.738	8.75	26.4
Boiler pumps	0.220	0.14	82.5
CRT pump	0.331	0.21	28.2
HPH1	0.438	0.28	97.4
HPH2	0.359	0.23	97.2
Deaerator	0.355	0.23	95.3
LPH4	0.377	0.24	89.5
LPH5	0.295	0.19	67.3



Refrence environment temperature (K).

Fig. 2-3. Effect of reference environment temperature on total exergy destruction rate in major plant components.

Exergy and percent of exergy destruction along with the exergy efficiencies are summarized in Table 5 for all components present in the power plant. It was found that the exergy destruction rate of the boiler is dominant over all other irreversibilities in the cycle. It counts alone for 77% of losses in the plant, while the exergy destruction rate of the condenser is only 9%. According to the first law analysis, energy losses associated with the condenser are significant because they represent about 66% of the energy input to the plant. An exergy analysis, however, showed that only 9% of the exergy was lost in the condenser. The real loss is primarily back in the boiler where entropy was produced. Contrary to the first law analysis, this demonstrates that significant improvements exist in the boiler system rather than in the condenser.

The calculated exergy efficiency of the power cycle is 25%, which is low. This indicates that tremendous opportunities are available for improvement. However, part of this irreversibility cannot be avoided due to physical, technological, and economic constraints

In order to quantify the exergy of a system, we must specify both the system and the surroundings.

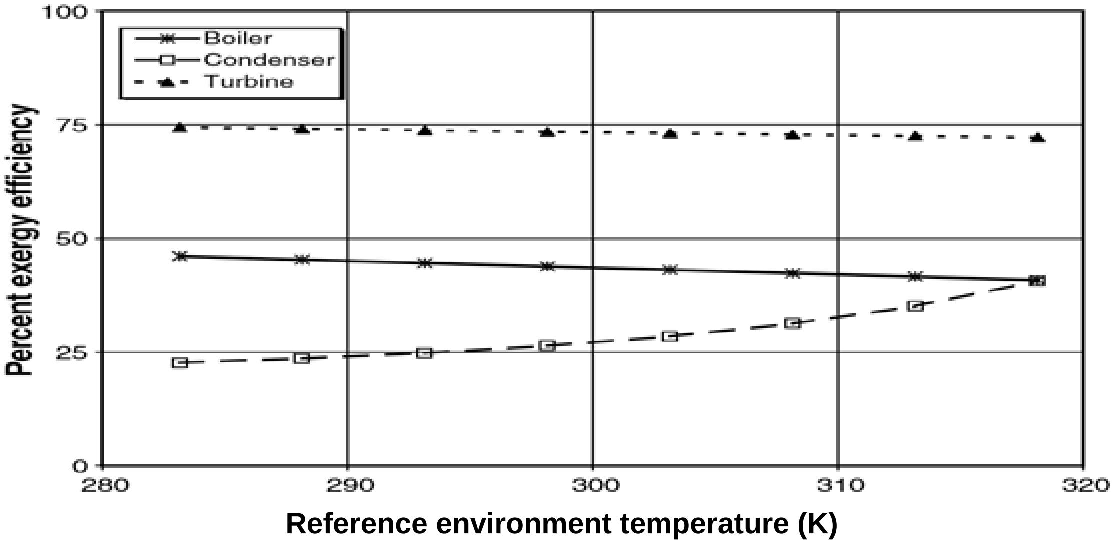


Fig. 2-4 Effect of reference environment temperature on the exergy efficiency of major plant components.

Intensive properties of the environment are not significantly changed by any process. The dead state is a state of a system in which it is at equilibrium with its surroundings. When a system is at the same temperature, pressure, elevation, velocity and chemical composition as its surroundings, there is no potential differences exist in such instances that would allow the extraction of useful work[14]. The reference environment state is irrelevant for calculating a change in a thermodynamic property (first law analysis). However, it is expected that the dead state will have some effects on the results of exergy (second law) analysis. Although, some researchers assumed that small and reasonable changes in dead-state properties have little effect on the performance of a given system. To find out how significant this effect will be on the results, the dead-state temperature was changed from 283.15 to 318.15 K while keeping the pressure at 101.3 kPa. Values of total exergy rates at different dead states for locations identified in Fig(2-3) that the major source of exergy destruction is the boiler no matter what the dead state is. Fig. (2-4) shows that exergy efficiencies of the boiler and turbine did not change significantly with dead-state temperature; however, the efficiency of the condenser at 318.15 K is almost twice as much when the ambient temperature was 283.15 K. This can be explained by noting the diminution of temperature difference between the steam and the cooling air as the dead-state temperature is increased. This will decrease the exergy destruction and hence, will increase the exergy efficiency.

CHAPTER THREE

ENERGY AND EXERGY ANALYSIS
OF
GARRI “4” POWER PLANT

3.1 Preface

First all details about Garri (4) power plant required to applied exergy analyzed in previous section (3.1); this part explains main information and all data at specified operation condition to Garri (4) power plant as the follow.

3.1.1 Location of garri (4)

Garri (4) located at the east from Garri (2) near phase II of Khartoum refinery which produce sponge coke.

This location has the following advantages:

- It is near Khartoum refinery to supply sponge coke.
- It is near garri (2) to connect garri (4) substation with garri (2) and national grid, also supply garri (4) with LDO and water from garri (2).

3.1.2 Operation data

Garri (4) is sponge coke fired power plant. It is afirst power plant in the middle east which used asolid fuel.

Khartoum refinery produces 256 ton/year of sponge coke as by product. This coke can be used to generate electric power. So NEC decided to build garri (4) power plant which used this coke as solid fuel.

Garri (4) is steam power plant, it works with regeneration cycle. It consists of two steam turbines each one generate 55 MW. Each turbine has a boiler to supply superheated steam to the turbine. This boiler known as a circulating fluidized bed boilers (CFB Boilers).

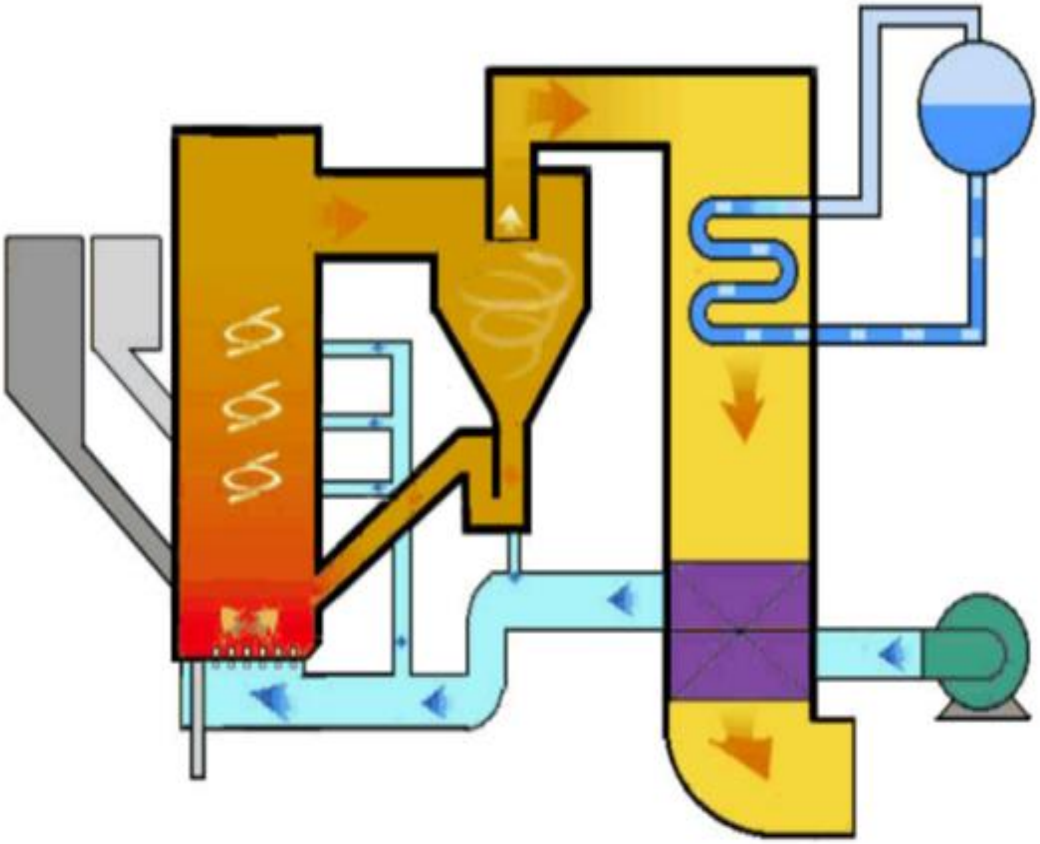


Figure 3.1 shows CFB boiler

3.2 Energy and Exergy analysis of steam cycle component

Exergy is a measure of the maximum capacity of a system to perform useful work as it proceeds to a specified final state in equilibrium with its surroundings. Exergy is generally not conserved as energy but destructed in the system. Exergy destruction is the measure of irreversibility that is the source of performance loss. Therefore, an exergy analysis assessing the magnitude of exergy destruction identifies the location, the magnitude and the source of thermodynamic inefficiencies in a thermal system.

3.2.1 Exergy analysis of turbine

Exergy balance in equation (2-6) applicable, assume fully adiabatic expansion flow hence term ((EX_Q)) will be zero, neglect mechanical transport and generator losses. Term $(\mathrm{EX_P})$ represents output power .and terms ($\sum_i m_i ex_i, \sum_e m_e ex_e$) can be calculated by equation (2-5).

3.2.2 Exergy analysis of condenser

Exergy balance in equation (2-6) applicable, assume fully adiabatic heat exchanging hence term ($(\mathrm{EX_Q})$) will be zero and there is no work; $(\mathrm{EX_P})$ equals zero .and terms ($\sum_i m_i ex_i, \sum_e m_e ex_e$) can be calculated by equation (2-5).

3.2.3 Exergy analysis of Boiler

The boiler system of the plant will be discussed in this calculation as two subsystems. The first subsystem is Burner where fuel combusted. The burner has two inlet streams which are fuel stream and air stream, also has one outlet stream which conveys hot products of combustion to a Heat exchanger which is considered as second subsystem.

The Heat exchanger subsystem is closed type heat exchanger. It contains two inlet streams, one of them is the hot products stream and the other is feed water stream. Also heat exchanger has two outlet streams which are steam outlet stream and Flue gases outlet stream.

3.2.4 Exergy analysis of Heater

Assume fully adiabatic and isobaric flow due to all stages in HRSG, Equation (2-13) applicable to calculate exergy destruction. Entropy generation at that equation is calculated by entropy balance .And To calculate exergy of escape flue gases due to chimney equation (2-5) applicable.

$$S_{in} - S_{out} + S_{gen} = \Delta S_{sys} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3-1)}$$

Steady flow rate; entropy change term (ΔS_{sys}) will be zero, hence

equation (3-1) becomes:

$$S_{gen} = S_{out} - S_{in} \qquad \text{(3-2)}$$

The four component of HRSG deals as a heat exchanger and should be analyzed individually to knowing distribution of exergy destruction on HRSG. Entropy out (term (S_{out})) represent entropy out on flue gases and steam water, calculated by equation (3-3). entropy in as well as entropy out, by equation (3-4).

$$S_{out} = m_{gas} s_{gas,e} + m_w s_{w,e} \qquad \text{(3-3)}$$

$$S_{in} = m_{gas} s_{gas,i} + m_w s_{w,i} \qquad \text{(3-4)}$$

Substitute (3-3), (3-4) in (3-2) and rearranged

$$S_{gen} = m_{gas}\left(s_{gas,e} - s_{gas,i}\right) - m_w\left(s_{w,e} - s_{w,i}\right) \qquad \text{(3-5)}$$

Term $\left(s_{gas,e} - s_{gas,i}\right)$ calculated by equation (3-6)

$$s_2 - s_1 = c_p \ln\frac{T_2}{T_1} - R\ln\frac{p_2}{p_1} \qquad \text{(3-6)}$$

Note: $\left(s_{w,e}, s_{w,i}\right)$ taken directly from steam table at specified state for each part in heat exchanger.

Mass, energy, and exergy balances for any control volume at steady state withnegligible potential and kinetic energy changescan be expressed, respectively, by

$$\sum m_i = \sum m_e \qquad \text{(3-7)}$$

$$Q - W = \sum m_e h_e - \sum m_i h_i \qquad \text{(3-8)}$$

$$X_{heat} - W = \sum m_e \Psi_e - \sum m_i \Psi_i + I \qquad \text{(3-9)}$$

where the net exergy transfer by heat(X_{heat}) at temperature T is given by

$$X_{heat} = \sum (1 - T_0/T)Q \qquad (3\text{-}10)$$

and the specific exergy is given by

$$\Psi = h - h_0 - T_0(S - S_0) \qquad (3\text{-}11)$$

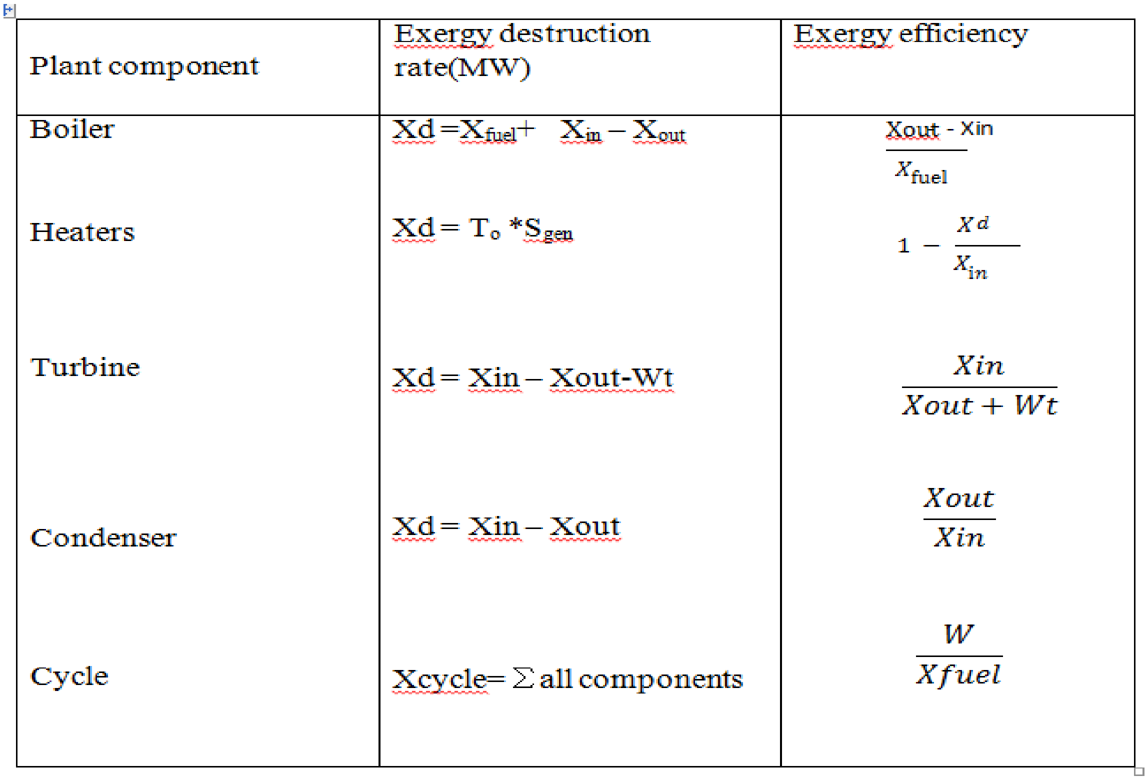
Then the total exergy rate associated with a fluid stream becomes

$$X = m\,\Psi = m(h - h_0 - T_0(S - S_0)) \qquad (3\text{-}12)$$

For a steady state operation, and choosing each component. as a control volume, the exergy destruction rateand the exergy efficiency are defined as shown in Table (3.1)The exergy efficiency of the power cycle may be defined in several ways, however, the used definition will not only allow the irreversibility of heat transfer to the steam in the boiler to be included, but also the exergy destruction associated with fuel combustion and exergy lost with exhaust gases from the furnace [17]. Note that the fuel specific exergy is calculated as: Ψ fuel = γf

LHV, where γf = 1.06, is the exergy factor based on the lower heating value.

Table 3-1 The exergy destruction rate and exergy efficiency equations for steam cycle power plant components .



Plant component	Exergy destruction rate(MW)	Exergy efficiency
Boiler	$X_d = X_{fuel} + X_{in} - X_{out}$	$\frac{X_{out} - X_{in}}{X_{fuel}}$
Heaters	$X_d = T_o * S_{gen}$	$1 - \frac{X_d}{X_{in}}$
Turbine	$X_d = X_{in} - X_{out} - W_t$	$\frac{X_{in}}{X_{out} + W_t}$
Condenser	$X_d = X_{in} - X_{out}$	$\frac{X_{out}}{X_{in}}$
Cycle	$X_{cycle} = \Sigma$ all components	$\frac{W}{X_{fuel}}$

Table 3.2: Operation data for steam turbine

Equipment	position	T(C)	P(bar)	m(kg/s)
Turbine	In	522	67.1	41.3
	Out	39.3	0.121	33.58
Condenser	In	39.3	0.121	33.58
	Out	39.3	0.121	33.58
Boiler	In	142.4	67.1	41.3
	Out	522	67.1	41.3
Heater1	In	39.3 61.9	3.46 3.46	1.44 39.85
	Out	61.9 61.9	3.46 3.46	0 41.3
Heater2	In	61.9 89.9	3.46 1.319	4.8 39.85
	Out	89.9 89.9	3.46 1.319	4.8 39.85
Heater3	In	89.9 124.4	3.46 0.75	4.91 36.49
	Out	124.4 124.4	3.46 0.75	4.91 36.49
Heater4	In	124.4 142.4	0.257 3.46	2.91 34.94
	Out	142.4 142.4	0.257 3.46	2.91 34.94
Pump1	In	39.3	0.121	33.58
	Out	39.3	3.46	33..58
Pump2	In	142.4	3.46	41.3
	Out	142.4	67.1	41.3

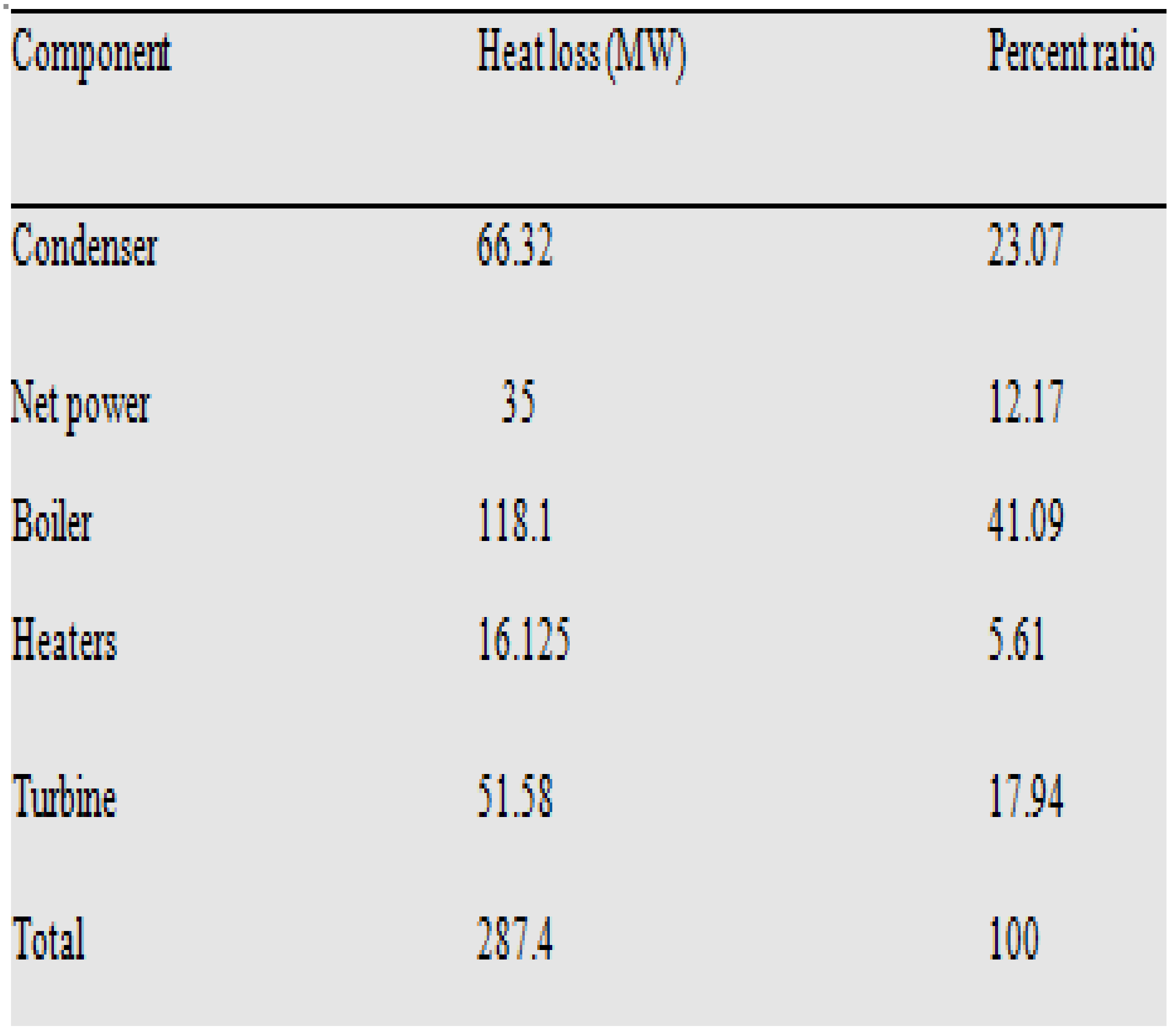
CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Preface

This chapter is present all results achieved for Garri(4) power plant as the follow. The energy and exergy losses and efficiency for the components of the Garri(4) power plant .The steam turbine cycle present by Table(4.1)and (4.2) the energy and exergy losses for all steam turbines component and appears that the greatest exergy losses in steam turbine cycle takes place at turbine unite due to irreversibilities and mechanical losses associated with transport power to electrical generator . The result is shown in Table(4.1)and (4.2)

Table (4.1) Energy balance of the GARRI(4) components and percent ratio to fuel energy input.



Component	Heat loss (MW)	Percent ratio
Condenser	66.32	23.07
Net power	35	12.17
Boiler	118.1	41.09
Heaters	16.125	5.61
Turbine	51.58	17.94
Total	287.4	100

Table (4.2) Exergy destruction and exergy efficiency of GARRI(4)components when To = 308 K, Po = 101.3 kPa

	Exergy destruction (MW)	Percent exergy destruction	Percent exergy efficiency
Boiler	73	80.21	41.9
Turbine	16.6	18.24	70.3
Condenser	1	1.1	1
Heaters	0.4	0.43	98.5
Power cycle	91	100	48

Exergy and percent of exergy destruction along with the exergy efficiencies are summarized in Table (4.1) for all components present in the power plant. It was found that the exergy destruction rate of the boiler is dominant over all other irreversibilities in the cycle. It counts alone for 80.21% of losses in the plant, while the exergy destruction rate of the condenser is only 1.1%. According to the first law analysis, energy losses associated with the condenser are significant because they represent about 23.07% of the energy input to the plant. An exergy analysis, however, showed that only 1.1% of the exergy was lost in the condenser. The real loss is primarily back in the boiler where entropy was produced. Contrary to the first law analysis, this demonstrates that significant improvements exist in the boiler system rather than in the condenser.

The calculated exergy efficiency of the power cycle is 12.17%, which is low. This indicates that tremendous opportunities are available for improvement. However, part of this irreversibility can not be avoided due to physical, technological, and economic constraints.

Figure (4-1) Shows exergy destruction rate of Garri(4), which large destruction found in boiler component and small destruction found in heaters.

And also figure (4-2) Shows exergy efficiencies for all main components of Garri (4) thermal power plant, which greatest efficiency found in heaters, although weak effect to heaters in general resultant to plant.

Figure (4-3) Shows contribution each part from components of Garri (4) plant in exergy destruction.

Figure (4-4) and (4-5) Show comparing in exergy destruction and exergy efficiencies between Alhussein and Garri(4), which Alhussein plant generates about 53MW , when Garri(4) plant generates 35MW.

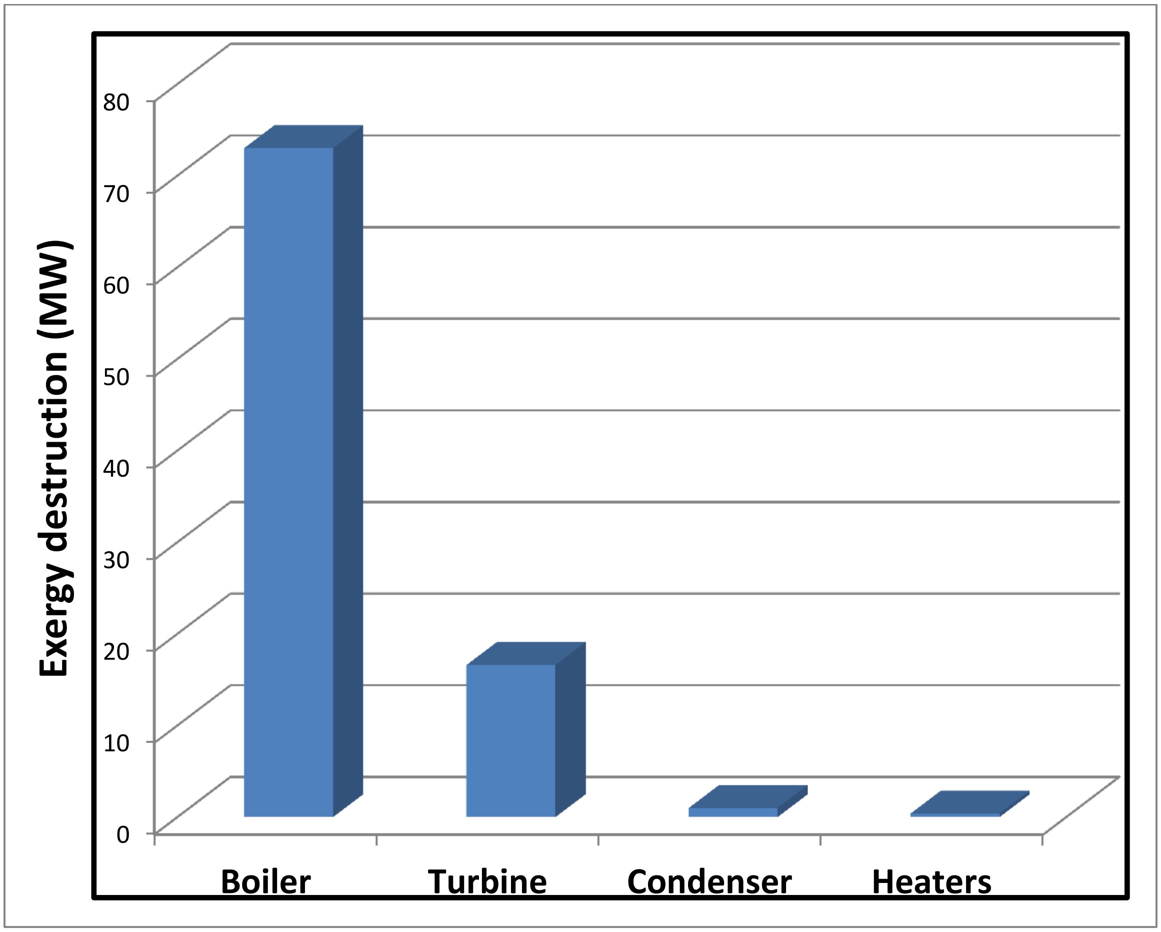


Fig (4-1) Exergy destruction rate of Garri(4)

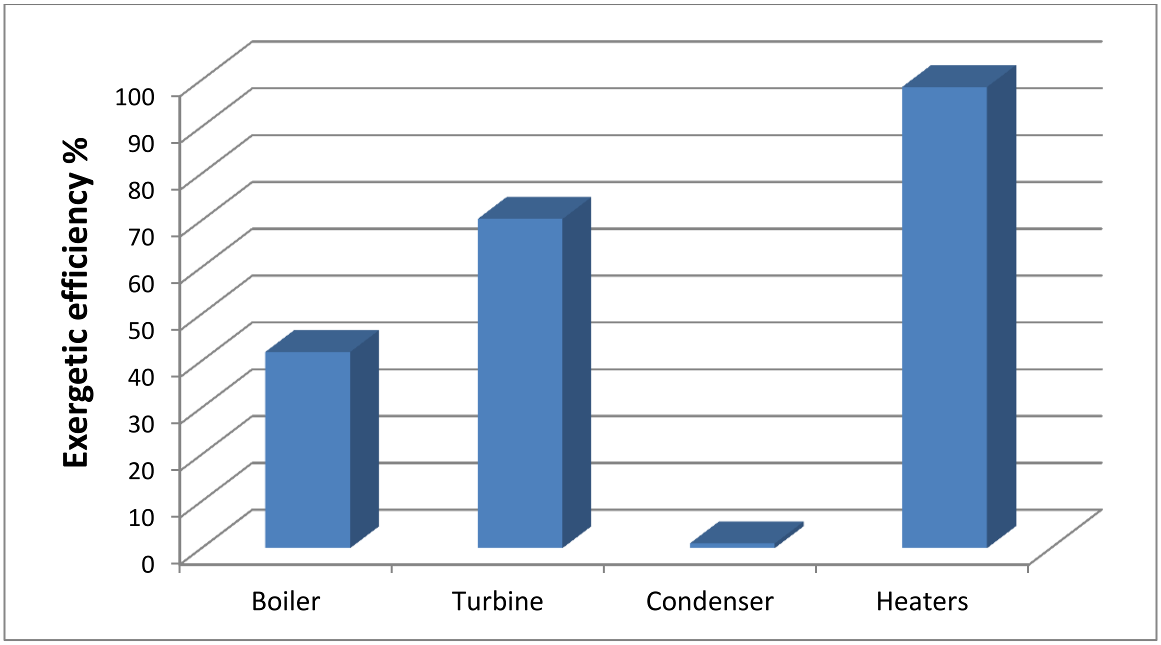
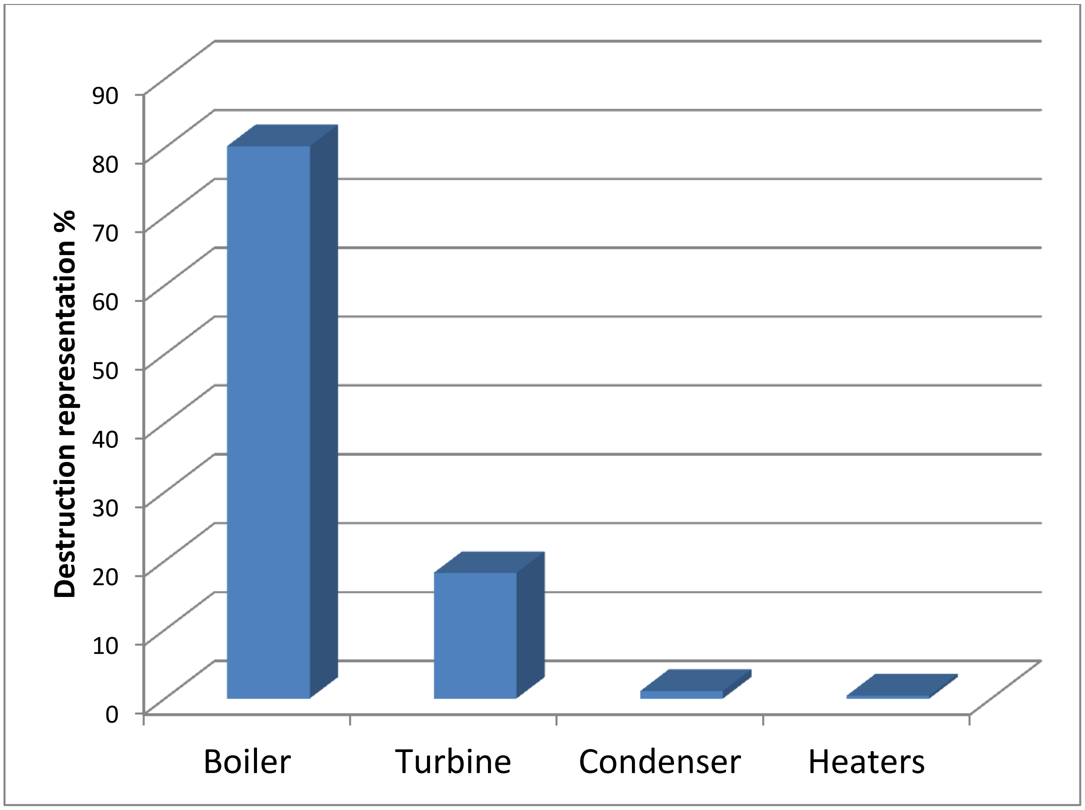
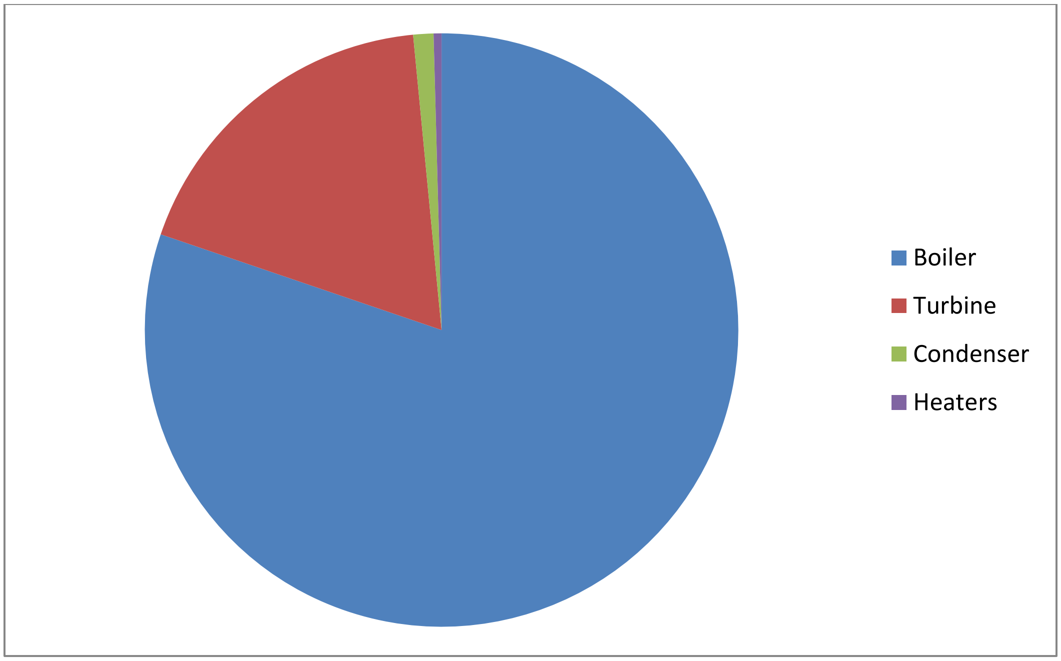


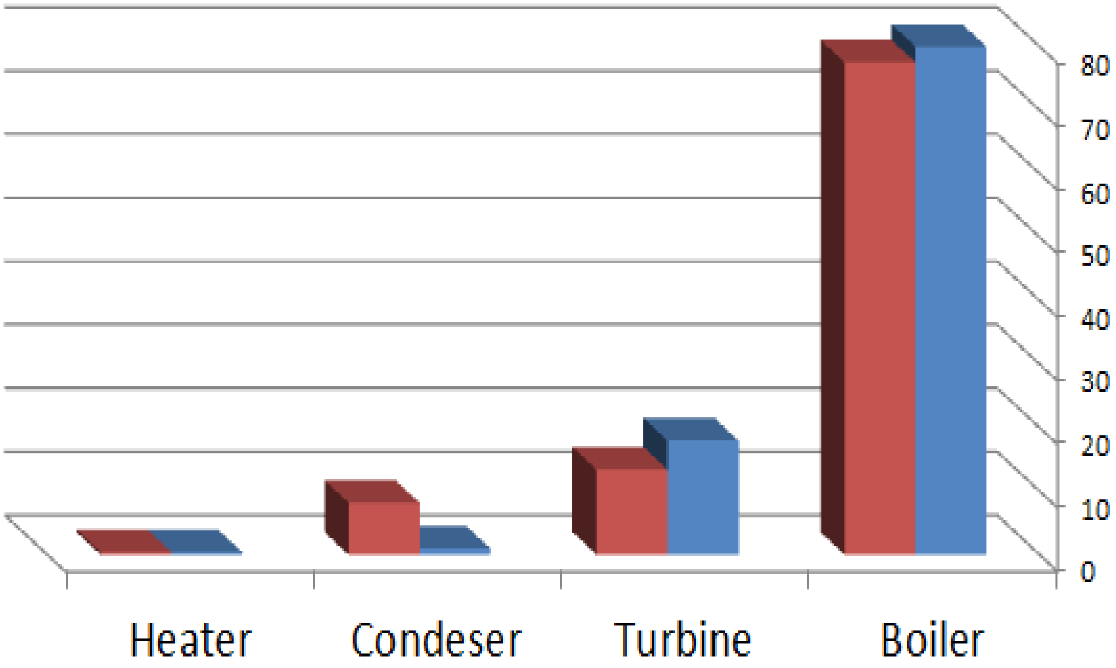
Figure (4-2) Exergetic efficiency of Garri(4)



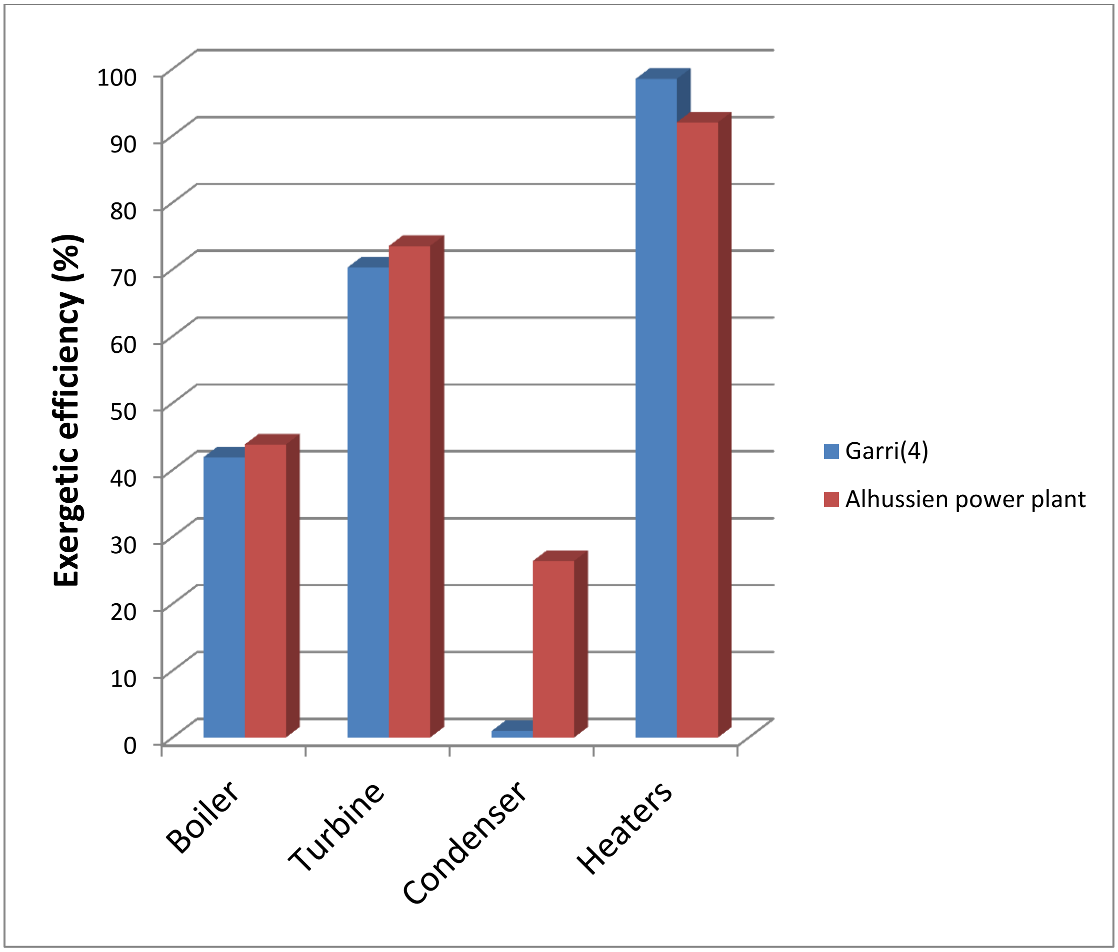
Fig(4.3) Contribute each part on exergy destruction for Garri(4)



Fig(4.4) Exergy destruction for all components of Garri(4)



Fig(4-5) Exergy destrution of Alhussein and Garri(4)



Fig(4-6) Exergy efficiency of Alhussien and Garri(4).

CHAPTER FIVE

CONCLUSION

&

RECOMMENDATIONS

5.1 Conclusion

In this study ,the maximum energy loss has been found to occur in the boiler ,where around 41% of the total power plant energy losses happen.

The second largest energy loss occurs in the turbine system which is about 18%. In addition the calculated thermal efficiency of the cycle was 31%.

The major exergy destruction has been found in the boiler where 80.21% of the total exergy destruction of the power plant cycle is destroyed.

However, 18.24% of the total exergy loss is due to the turbine and 1.1% of the total exergy loss is due to the condenser and less than 1% of the total exergy loss is due to the heaters and pumps.

The calculated exergy efficiency of the power plant cycle was 27%.

The major source of exergy destruction was the boiler system,where chemical reaction is the most significant source of exergy destruction in acombustion chamber.

5.2 Recommendations

- Our country sudan in present will confront high shortage in total electrical energy produced ,so we have to benefit from all the pwer plants that we have to produce maximum electrical energy and establish new power plants as GARRI(4), because this plant is used cheap fuel to produce electrical energy to make balance between cost and price of produced electrical energy.
- From this research appear that the optimization of combustion chamber have an important role in reducing exergy ,so we have to find ways to resolve this problem.

- The maximum electrical energy that we can producing from GARRI(4) power plant is 55 MW , but now the actual produced electrical energy is 35 MW , this losses in energy due to many reasons ,but main reason is viberation problem in turbine .which breaking happened in turbine blades so experts team recommended to operate this plant at load 35 MW just to avoid other problems will happen for this plant at load 55 MW , so should be to maintenance this problems in turbine.
- Also we have problems in sand line , this will require continued maintenance , so we have to choice and design new sand line or modify in some parts of this line till contribute to getting cheap energy from this plant.
- Also, we have to respect surrounding environment around this plant, that by operate(ESB) system to absorb (ASH) before to escape through chimney, and then we can to add some substances and elements to this to get bituminous , and this will represent income source to this plant instead of to be polluted source to environment.

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