SUDAN UNIVERSITY
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Energy and Exergy Analysis for Khartoum North Power Station Phase (6)

تحليل الطاقة والاكسيرجي في محطة كهرباء الخرطوم شمال-الوحدة السادسة

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 wife who gives me wormed life

Acknowledgement

First of all I would like to submit my best greeting to my supervisor Dr. **A .A.A.Abueinuor** for his acceptance to supervise my research and for his directions during preparing this research. Alsomy full respect and appreciation to all friends, colleagues and co-workerenhanced me in this research and helped me in data collection stage. Finally, a lot of thanks to Khartoum North Power Station Directorate which gives me permeations to apply this research and analysis in the station and has been supplying me by all data I needed throughout the research.

Abstract

The power industries, especially thermal power plants, have large energy consumptions, which play an important role in energy conversion. In this study, the energy and exergy analysis of Khartoum North power plant in sudan is presented. The primary Objectives of this research are to analyze the system components separately and to identify and quantify the sites having largest energy and exergy losses. In addition, the effect of varying the reference environment state on this analysis will also be presented. The performance of the plant was estimated by a component wise modeling and a detailed break-up of energy and exergy losses for the considered plant has been presented. Energy losses mainly occurred in the condenser where 18MW is lost to the environment while 36MW 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 (43%) followed by the turbine (8%), and then the forced draft fan condenser (28%). 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 77%. 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.

المستخلص :

الصناعات لها معدل استهلاك عالي لطاقة خاصه محطات الطاقة الحراريه التى تلعب دوراً هاما في تحويل الطاقة .في هذه الدراسه تم تحليل الطاقة والاكسيرجي للمحطة كهرباء الخرطوم شمال الاهداف الرئيسيه لهذا البحث هي تحليل مكونات النظام كل على حدة وقياس اكبر الخسائر في الطاقة والاكسيرجى بلاضافة الى ذلك سيتم ايضاً عرض تاثير تغير درجةحرارة البيئه المحيطه في هذا التحليل .

تم تقيم اداء المحطة بواسطة تحليل الطاقة ولاكسيرجي لمكونات المحطة ووجدت خسائر الطاقة بشكل رئيسى في المكثف 18 ميقاواط للبيئه في حين خسر المرجل 36 ميقاواط ثم اعلى نسبة اكسيرجي في المرجل 43 % يليه المكثف 28% ثم التوربين 8% .الكفاءة الحراريه محسوبه علي اساس القيمة الحراريه ولوحظ ان التفاعل الكيميائى هو اهم مصدر للدمار الاكسيرجي في نظام المرجل ويحد من تسخين الهواء وتخفيض نسبة الهواء والوقود.

Contents

CHAPTER ONE

INTRODUCTION

1.1 Background

The increased awareness that the world's energy resources are limited has caused many countries to reexamine their energy policies and take drastic measures in eliminating waste [1]. In recent years, the role of combustion engines technology in human life has been highlighted because over 80% of worldwide energy demand has been fulfilled by combustion methods. The augmentations in combustion efficiency and pollutant reduction have become the main concerns of combustion researchers in academic societies and of industrial manufacturers. In the combustion process, a reaction between the fuel and the oxidizer occurs to release heat (thermal energy) and consequently generate electricity. Current researchers focus on increasing combustion performance while reducing the emission of these pollutants. The most important factor driving the increasing focus on combustion performance is energy savings because the anticipated global energy demand is expected to rise by 58% between 2001 and 2025. Figure 1.1 shows the world's energy production by source [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. Although between 2001 and 2025 the global production of renewable energy is expected to rise by 8%, the expected annual growth of energy demand will rise by 1.9% [3, 4].

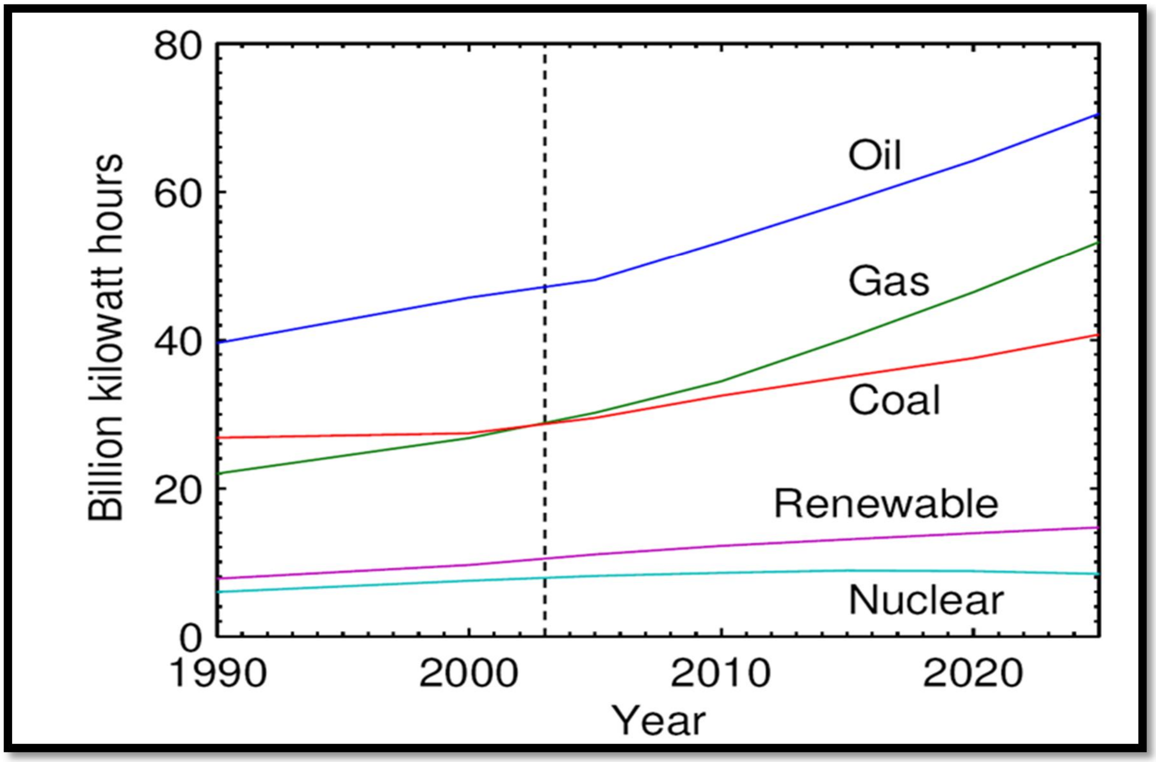


Figure 1.1: World energy productions by sources [2].

Most of the investigations have focused on increasing combustion performance by conserving energy. The first law of thermodynamics deals with the quantity of energy and asserts that energy cannot be created or destroyed. This law merely serves as a necessary tool for the bookkeeping of energy during a process and offers no challenges to the engineer. The second law, however, deals with the quality of energy. More specifically, it is concerned with the degradation of energy during a process, the entropy generation, and the lost opportunities to do work; and it offers plenty of room for improvement [1]. The second law of thermodynamics has proved to be a very powerful tool in the optimization of complex thermodynamic systems.

The optimization of power generation systems is one of the most important subjects in the energy engineering field. Due to the high prices of energy and the decreasing fossil fuel resources, the optimum application of energy and the energy consumption management methods are very critical. The combined cycle power plants (CCPPs) have higher thermal efficiency than the separate steam and gas turbine cycle power plants [2]. 80% from electricity energy produced from fired thermal power plant [5] hence non renewable energy (fossil fuel) so that the world aware about the optimum use for this reserve. First law of thermodynamics awarded criteria to energy transfer using energy balance whereas the second law of thermodynamics gives us more insight to evaluate efficient of thermal engineering systems using first law efficiency and second (exergy) efficiency. Exergy is defined as the maximum theoretical useful work that can be obtained as a system interacts with an equilibrium state. The exergy is not generally conserved like energy but is destroyed in the system. Exergy calculation shows the place in the system where losses occur and the magnitude of these losses. Thermal efficiency of engineering systems calculated by the rational between output and input no matter about maximum theoretical efficiency (Carnot efficiency) whilst exergy efficiency calculated by the rational between thermal efficiency and maximum theoretical efficiency to knowing the portion from available energy destroyed due to inefficient processes. The thermal power plant are widely used in Sudan grid net work, Khartoum North Power Station Phase (6)" consider one from these plants producing about 100 MW in design condition this study aimed to estimate exergy destruction due to processes individually and calculate exergy efficiency to know who 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 (Khartoum North Power Station(phase(6))an existing 100 MW (fuel-fired) electrical steam cycle power plant to identify the potential for improvement.

1.4 Scope

Energy and exergy destruction to main equipment (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

LITREATURE REVIEW

2.1 Introduction

A power plant is plying very important role in engineering field (also referred to as a generating station, power station, powerhouse, or generating plant) is an industrial facility for the generation of electric power. Most power stations contain one or more generators, a rotating machine that converts mechanical power into electrical power. The relative motion between a magnetic field and a conductor creates an electrical current. The energy source harnessed to turn the generator varies widely. Most power stations in the world burn fossil fuels such as coal, oil, and natural gas to generate electricity. Others use nuclear power, but there cleaner renewablesourcessuchas solar, wind, wave and hydroelectric[6,7,8].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[1]. 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 [9]. 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?

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 [10]. 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 [11]. 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 [12]. 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 [13]. As a matter of fact, many researchers [14–17] 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 [12]. 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 [18]. Some researchers dedicated their studies to component exergy analysis and efficiency improvement [19,20]; others focused on systems design and analysis [21–25]. 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.

2.2 **Plant description**

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 (2-1) Properties of heavy fuel oil used in Al-Hussein power plant for April2007[30]

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 in Fig. 1. 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). Then output air

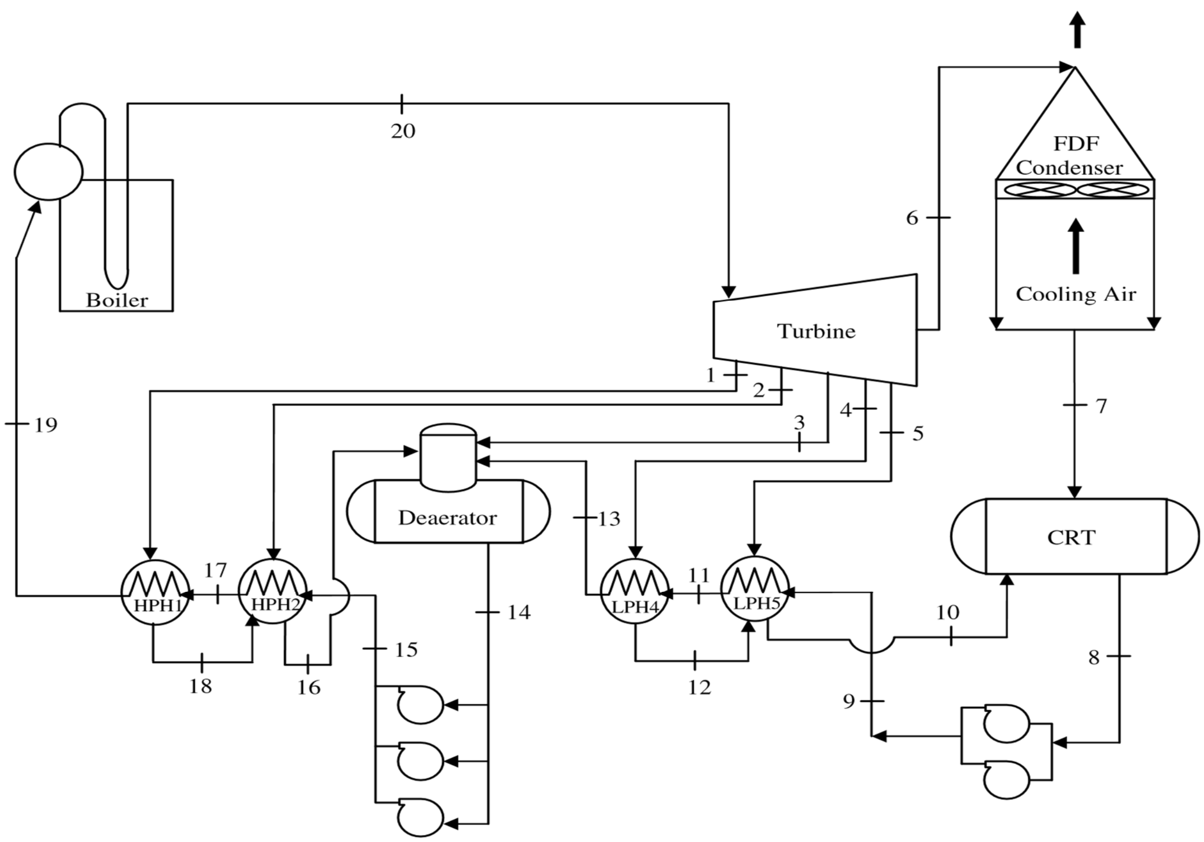


Fig. 1. Schematic diagram of the power plant.

Fig 2-1 schematic diagram of Al-Hussein power plant

Table(2- 2) Operating conditions of the power plant[30]

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

2.3 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 [26].

2.3.1 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 [26]:

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

Physical exergy is defined as the follow [27]:

$$ex_{ph} = ex_T + ex_p \quad \text{.................................... (2-2)}$$

$$ex_T = c_p\left[(T - T_0) - T_0 \ln\left(T/T_0\right)\right] \quad \text{...................... (2-3)}$$

$$ex_P = RT_0 \ln(T/T_0) \quad \text{.................................. (2-4)}$$

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

$$ex_{ph} = (h - h_0) - T_0(s - s_0) \quad \text{.. (2-5)}$$

If one applies the first and second laws of thermodynamics, one can find the formula for exergy balance as [26, 28].

$$EX_Q + \sum_i m_i ex_i = \sum_e m_e ex_e + EX_P + EX_d \quad \text{....................... (2-6)}$$

$$E\ X_Q = \left(1 - T_0/T_i\right) Q_i \quad \text{................................ (2-7)}$$

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

The chemical exergy for gas mixtures is defined as follows [28]:

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

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 [26, 28]:

$$\xi = ex_f/LHV_f \quad \text{.. (2-10)}$$

The ratio of chemical exergy to LHV_f is usually close to unity. In general fuel with chemical formula C_xH_y.

For gaseous fuels [26]:

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

For liquid fuels [13]:

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

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.

$$EX_d = T_0 S_{gen} \qquad \text{(2-13)}$$

2.3.2 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.

2.3.2.1 Thermal efficiency

The fraction of the heat input that is converted to net work 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 Q_{in} heat is rate transferred to the heat engine from a high temperature reservoir at T_H, and Q_{out} is rate heat rejected to a low temperature reservoir at 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

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

2.3.2.3 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).

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

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

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

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

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

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

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

2.4 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% [29]. 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 [30].

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(2-3) Energy balance of the power plant components and percent ratio to fuel energy input [30]

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 (2-4) Exergy destruction and exergy efficiency of the power plant components when To = 298.15 K, Po = 101.3 kPa [30]

	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

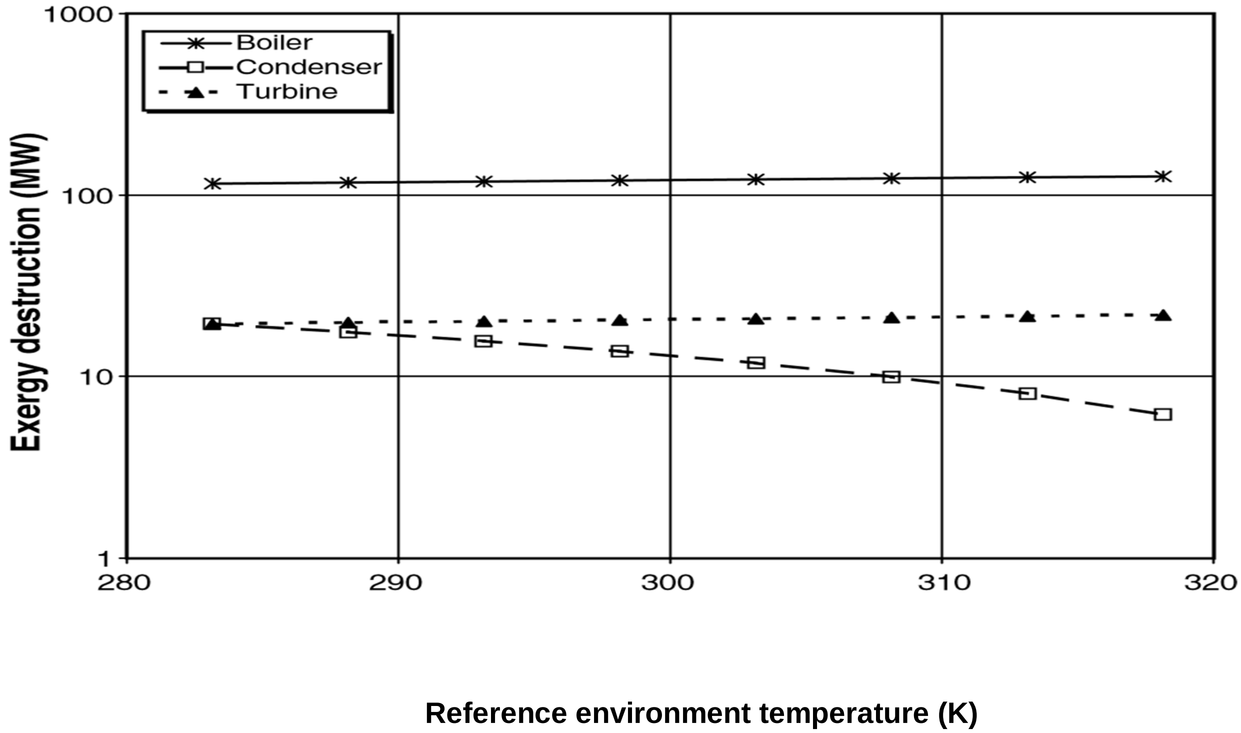


Fig. 2-2. Effect of reference environment temperature on total exergy destruction rate in major plant components.[30]

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 can not 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. It is assumed that the

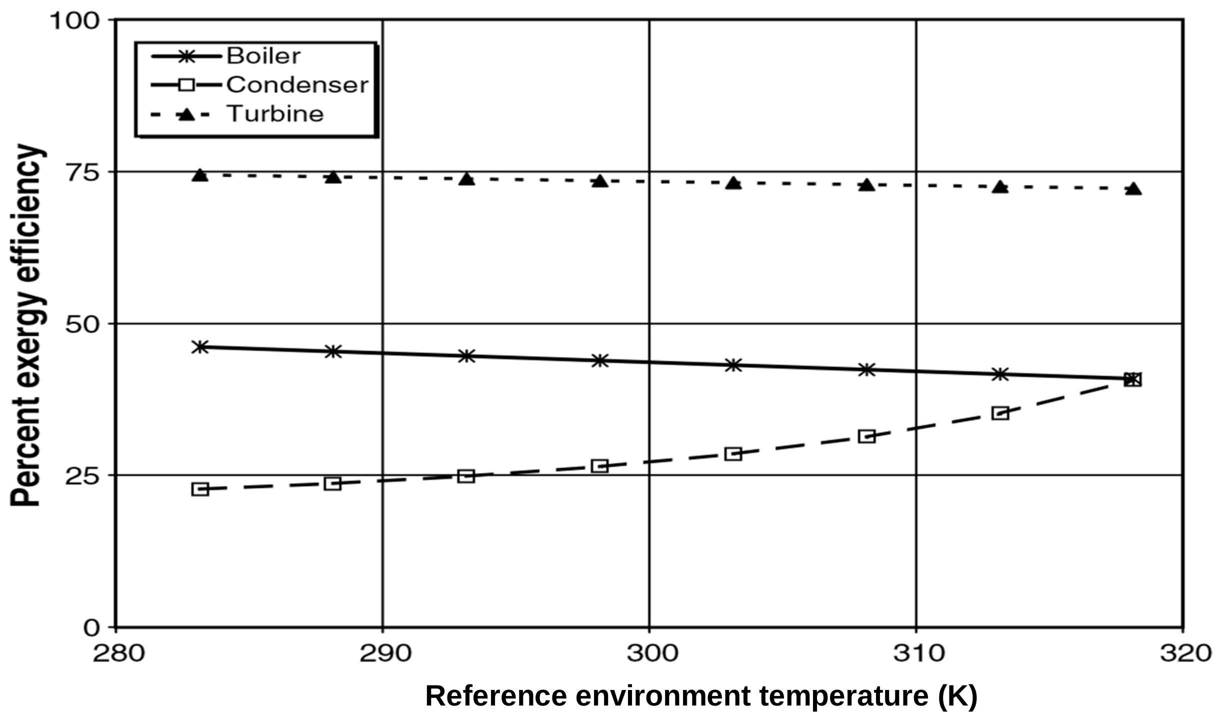


Fig. 2-3 Effect of reference environment temperature on the exergy efficiency of major plant components.[30]

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 [12]. 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.(2-1) Results of such analysis show, in Fig(2-2) that the major source of exergy destruction is the boiler no matter what the dead state is. Fig. (2-3) 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

Khartoum North Power Station Phase (6)

3.1 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.

3.1.1 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 (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).

3.1.2 Exergy analysis of condenser

Exergy balance in equation (2-6) applicable, assume fully adiabatic heat exchanging hence term ((EX_Q)) will be zero and there is no work; (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).

3.1.3 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.

3.1.4 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.

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

Steady flow rate; entropy change term (ΔS_{sys}) will be zero, hence equation (3-1) becomes:

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

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).

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

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

Substitute (3-14), (3-15) in (3-13) and rearranged

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

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

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

Note: $(s_{w,e}, s_{w,i})$ taken directly from steam table at specified state for each part in heat exchanger [21].

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

$\sum m_i = \sum m_e$ ……………………………………………………(3-7)

$Q - W = \sum m_e h_e - \sum m_i h_i$ ……………………………………(3-8)

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

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

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

and the specific exergy is given by

$\Psi = h - h_0 - T_0(S - S_0)$……………………………………………..…(3-11)

Then the total exergy rate associated with a fluid stream becomes

$X = m\,\Psi = m(h - h_0 - T_0(S - S_0))$……………………………………(3-12)

For a steady state operation, and choosing each component in Fig(2-1). 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 [18]. In addition, the pump input power was calculated as

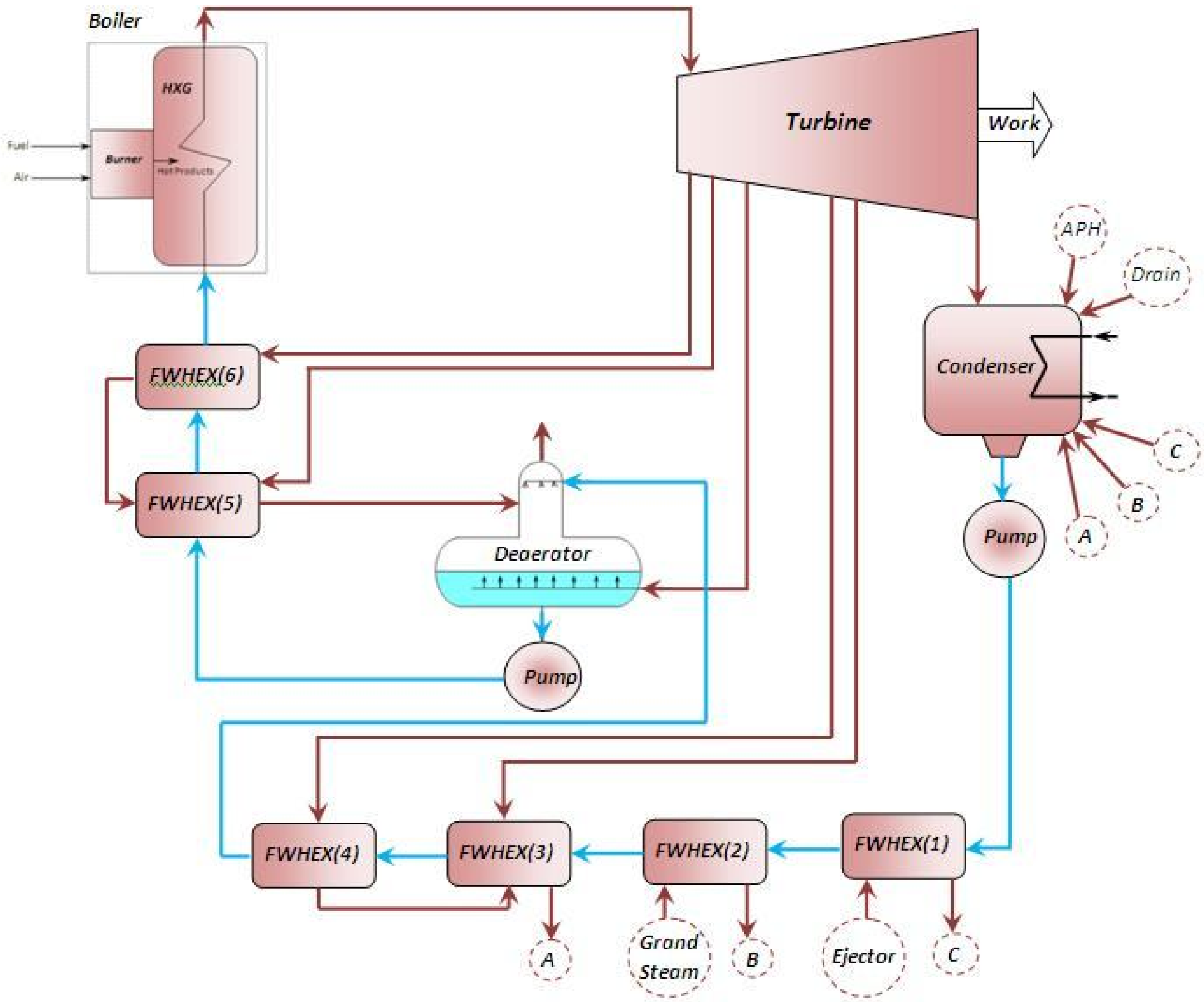


Figure 3.1 The schematic diagram of {KNPSP(6)}

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	$Xd = X_{fuel} + X_{in} - X_{out}$	$\frac{Xout - Xin}{X_{fuel}}$
Pumps	$Xd = X_{in} - X_{out} + W_{pump}$	$1 - \frac{X_d}{Wpump}$
Heaters	$Xd = X_{in} - X_{out}$	$1 - \frac{Xd}{X_{in}}$
Turbine	$Xd = Xin - Xout - Wt$	$1 - \frac{Xd}{Xin - Xout}$
Condenser	$Xd = Xin - Xout + W$	$\frac{Xout}{Xin + W}$
Cycle	$Xcycle = \sum$ all components	$\frac{W}{Xfuel}$

3.2 Applied energy and exergy analysis on KNPSP(6)power plant

First all details about KNPSP(6)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 KNPSP(6)power plant as the follow.

3.2.1 Plant Description

The Khartoum North Power Station Phase(6) (KNPSP(6)) has a total installed power capacity of (200) MW. It is located in Industrial Area district, in Khartoum, Sudan. It started to produce power in the end nineties. The power house consists of two steam turbines units (2x100) MW at 100% load. The KNPSP(6) uses Heavy cocker gas oil. The schematic diagram of one (100) MW unit at 100% load is shown in Figure 3.1

This unit employs regenerative feed water heating system. Feed water heating is carried out in six closed heat exchangers and one open heat exchanger (Daerator). The first closed heat exchanger receives hot stream from outlet of ejector and the second closed heat exchanger receives hot stream from outlet of gland steam system. The extracted steam streams from the turbine are distributed along the other four closed heat exchangers and Daerator as hot streams. Steam is superheated to 538 ℃ and 84.70 bar in the Boiler and fed to the turbine. exhaust stream at pressure 0.11 bar and it exhausts to a water cooled condenser operates . Then, the cycle starts over again.

3.2.2 Operation data

The main fuel uses in Khartoum North Power Station Phase(6) (KNPSP(6)) heavy fuel oil, which is obtained from a nearby oil refinery. The annual fuel consumption 437 TON Properties for the heavy fuel oil obtained are shown in Table 1

Table 3.2: Main data for KNPSP(6)

Parameter	Quantity
Heave fuel oil	890.3 kg/m^3
Fuel oil flow	20T/h
Air flow	261T/h
Air/fuel ratio	13
Feed water flow	286T/h
Steam flow	283T/h
Environment temperature	31C°

Table 3.3: Operation data for steam turbine

Equipment	position	T(K)	P(bar)	m(kg/s)
turbine	In	811	72.8	10.83
	Out	313	0.11	8.67
condenser	In	313	0.11	8.67
	Out	313	0.11	8.67
Boiler	In	490	84.7	8.67
	Out	811	72.8	10.83
LPHS	In	313	21	10.83
	Out	433	7	10.79
HPHS	In	433	84.7	10.79
	Out	490	84.7	8.67
Boiler feed pump	In	433	7	8.67
	Out	433	84.7	8.67

CHAPTER FOUR

RESULTS AND DISCUSSIONS

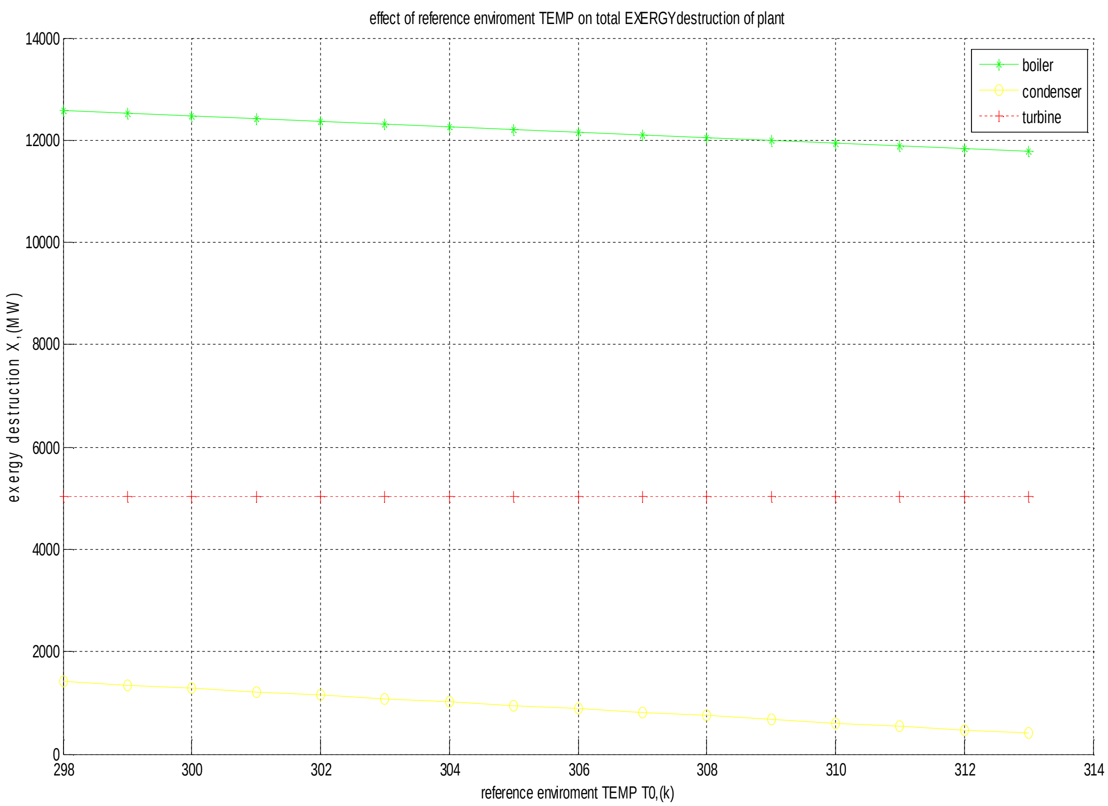
This chapter is present all results achieved for Khartoum North Power Station Phase(6) as the follow. The energy and exergy losses and efficiency for the components of the Khartoum North Power Station Phase(6) The steam turbine cycle present by Table(4.1)and (4.2) the energy and exergy losses for all 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 KNPSP(6) components and percent ratio to fuel energy input

Component	Heat loss (MW)	Percent ratio
Condenser	17.030	13
Net power	18.53	14.1
Boiler	35.560	27.05
Boiler pumps	0.0734	0.056
LPHS	22.303	16.96
HPHS	23.584	17.94
Turbine	14.386	10.94
Total	131.46	100

Table (4.2) Exergy destruction and exergy efficiency of **KNPSP(6)**components when To = 403 K, Po = 101.3 kPa

	Exergy destruction (MW)	Percent exergy destruction	Percent exergy efficiency
Boiler	29.684	42.33	51.56
Turbine	5.033	7.18	65.01
Condenser	19.339	27.58	45.62
Boiler pumps	0.151	0.215	99.6
LPHS	6.521	9.30	70.76
HPHS	9.39	13.39	60.19
Power cycle	70.12	100	77.6

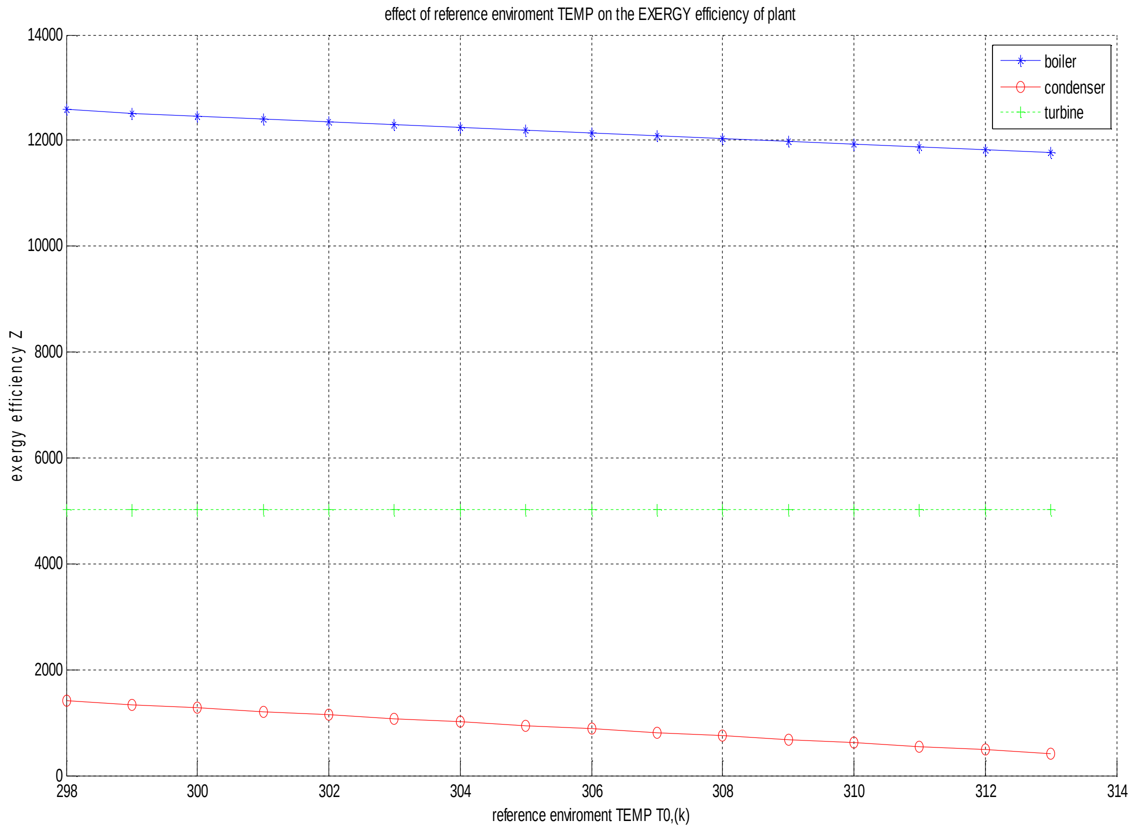


Fig(4-1) Effect of reference environment temperature on total exergy destruction rate in major plant components.

Exergy and percent of exergy destruction along with the exergy efficiencies are summarized in Table (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 42.33% of losses in the plant, while the exergy destruction rate of the condenser is only 27.58%. According to the first law analysis, energy losses associated with the condenser are significant because they represent about 13% of the energy input to the plant. An exergy analysis, however, showed that only 27.58% 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.

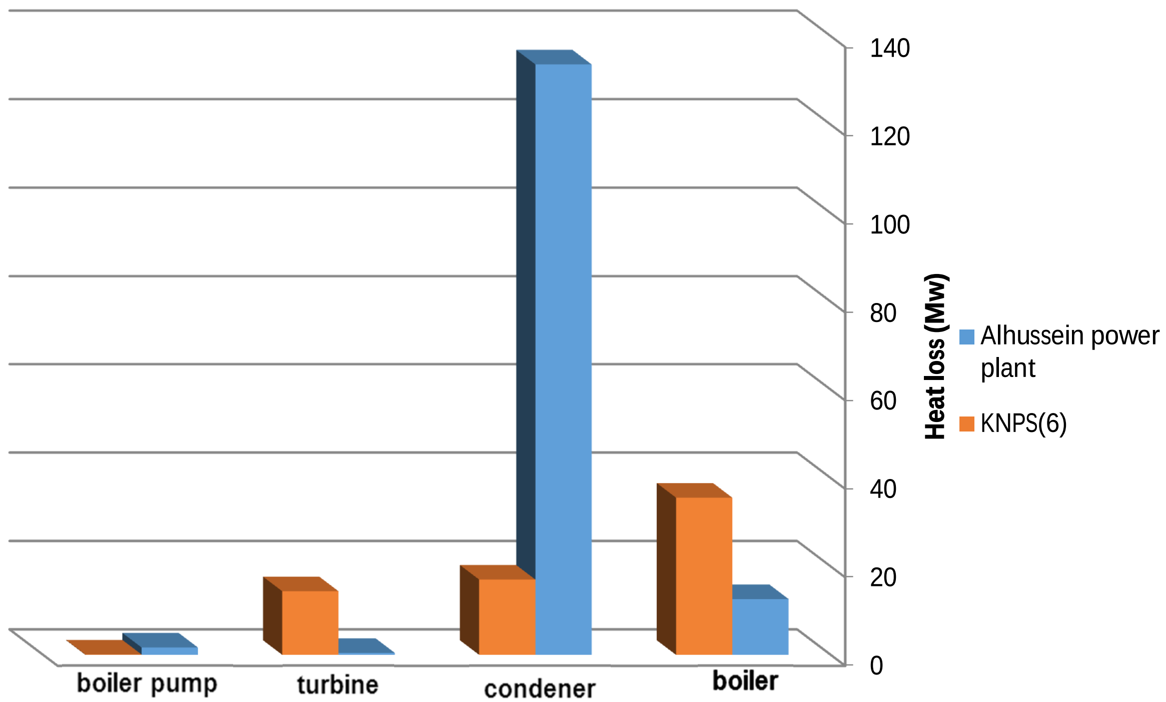
The calculated exergy efficiency of the power cycle is 14.1%, which is low. This indicates that tremendous opportunities are available for improvement. However, part of this irreversibility can not be avoided due to physical, technological, and economic constraints

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

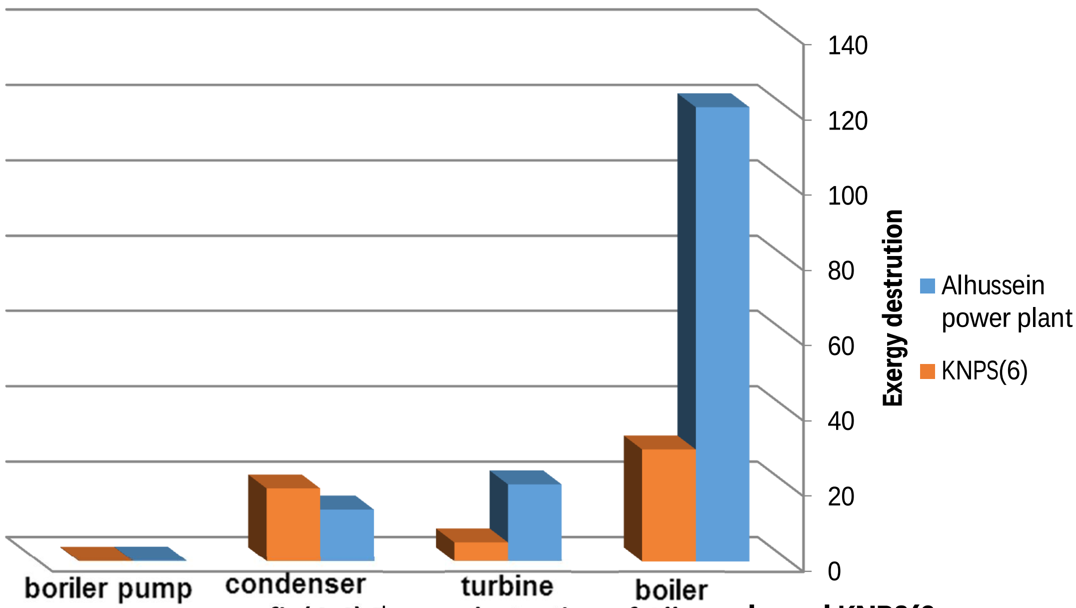


Fig(4-2) Effect of reference environment temperature on the exergy efficiency of major plant components.

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 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 298 to 314 K while keeping the pressure at 101.3 kPa. Values of total exergy rates at different dead states for locations identified in Fig.(4-1) Results of such analysis show, in Fig(4-2), that the major source of exergy destruction is the boiler no matter what the dead state is. Fig. 3 shows that exergy efficiencies of the boiler and turbine and condenser did not change significantly with dead-state temperature.



fig(4-3)Heat loss of Alhussein and KNPS(6)



fig(4-4) Exergy destrution of Alhussein and KNPS(6)

CHAPTER FIVE

CONCLUSION

&

RECOMMENDATIONS

5.1 Conclusion

In this study, an energy and exergy analysis as well as the effect of varying the reference environment temperature on the exergy analysis of an actual power plant has been presented. In the considered power cycle, the maximum energy loss was found in the boiler where 27.05% of the input energy was lost to the environment. Next to it was the energy loss in the condenser system where it was found to be about 13%. In addition, the calculated thermal efficiency of the cycle was 14.1%. On the other hand, the exergy analysis of the plant showed that lost energy in the condenser is thermodynamically

insignificant due to its low quality. In terms of exergy destruction, the major loss was found in the boiler system where 42.33% of the fuel exergy input to the cycle was destroyed. Next to it was the turbine where 5.033MW of exergy was destroyed which represents 7.18 % of the fuel exergy input to the cycle. The percent exergy destruction in the condenser was 27.58 % while all heaters and pumps destroyed less than 14%.

The calculated exergy efficiency of the power cycle was 77%, which is low compared to modern power plants. The major source of exergy destruction was the boiler system where chemical reaction is the most significant source of exergy destruction in a combustion chamber. Exergy destruction in the combustion chamber is mainly affected by the excess air fraction and the temperature of the air at the inlet. The inefficiencies of combustion can be reduced by preheating the combustion air and reducing the air–fuel ratio. Although the percent exergy destruction and the exergy efficiency of each component in the system changed with reference environment temperature, the main conclusion stayed the same; the boiler is the major source of irreversibilities in the syste

5.2 Recommendations

- To judge how good a power plant performance is , should know its actual work, irreversibility and second-law efficiency. Then selection of a power plant would be built in specified area should be after collection of data about avarege temperature and pressure along year and then semulate the power plant performance in different period along year to get average actual work, irrevesibility and second-law efficiency. Thus, it is sintifcly descision will be taken about how good potential to build this power plant in this specified area.

- For power plant complex operation , it is normal to decide what thermal power plant between manyare available in the complex should be shared into grid . like this decision sometimes is taken based on availability of the thermal plant where maintenance records and so on. But for econimical operation , the lower the power plant irreversibility is the better the best selection.thus it is important to know as operating engineer or operation manager the irreversibility of each thermal power plants in the complex to enssure efficient operation decisions are taken.
- Closed monitering for power plant performance is not easy job; but by using exergy analysis in power plant periodecly , it is possible to know at what component of the plant irrevesibility increases. Thus there is opertunity to enhence thermal efficiency of plant by replacing this component or applying deferent maintenance.
- As extention for this research, there is need to conduct comperhancive study such what had been done in this research in all power plant in the Sudan to moniter all where efficient performance. The essensial matter behind these efforts is to enssure econimical operation and lost energy means unnecessary additional cost.
- Add more of the heat exchanger in order to raise the efficiency of the condenser.

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