EXERGY ANALYSIS OF GAS TURBINE POWER PLANT IN IRAQ AL NAJAF

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EXERGY ANALYSIS OF GAS TURBINE POWER PLANT IN IRAQ AL NAJAF

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ABSTRACT

EXERGY ANALYSIS OF GAS TURBINE POWER PLANT IN IRAQ AL NAJAF

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The exergy analysis of Al Najaf power plant of capacity 115.74MW which is located in Iraq will present in this study. The analysis of every component in the system apart was tested in accordance with the laws of mass and energy conversion was one of the main goals of this thesis. As well as we will identify and quantify the sites which have exergy losses. This analysis provides an alternative plan to ensure superior performance of a power plant. The aspects under consideration were the quantitative exergy balance for the entire system and for each component, respectively. At different temperatures, rate of irreversibility of system components, efficiency of exergy and the efficiency flaws were highlighted for each component and for the whole plant. The exergy flow of a material is classified into the groupings of thermal, mechanical and chemical exergy in this study and a stream of entropy-production. Fuel Natural gas of low heating value of 50050 kJ/kg was used as the fuel. The evaluation addressed the question of how the fluctuations in cycle temperatures influence the exergetic efficiency and exergy destruction in the plant.

The rate of exergy destruction in the turbine was around 2.75% whereas that in the combustion chamber was about 55.77%. When a 8°C rise was done in the temperature, exergy efficiency for the combustion chamber was calculated to be 49.83%. According to the results of the study, the combustion chamber is found to be chief means of irreversibilities in the plant. Also, it was identified that the exergetic efficiency and the exergy destruction are considerably dependent on the alterations in the turbine inlet temperature. On the basis of these results, recommendations are presented for advancement of the plant.

Keywords: Exergy Analysis, Efficiency; Irreversibility, Gas Turbine, Performance.

ÖZ

IRAK AL NAJAF ‘ DAKİ GAZ TÜRBİNLİ ELEKTRİK SANTRALİNİN EKSERJİ ANALİZİ

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M. Sc. Makine Mühendisliği Bölümü
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Bu çalışmada Irak’ da yerleşik 115.74MW kapasiteli Al Najaf elektrik santralinin ekserji analizi yer alacaktır. Sistemdeki her bileşenin analizi ayrı ayrı kütle kanunlarına göre yapılmış olup, enerji dönüşümü konusu bu tezin başlıca hedeflerinden biridir. Bu çalışmada aynı zamanda ekserji kayıplarının yaşandığı sahaları da tanımlayacağız ve miktarını belirleyeceğiz. Bu analiz bir elektrik santralinin en üstün seviyede performans göstermesini sağlayacak bir alternatif plan sunmaktadır. Çalışma çerçevesinde incelenen yönler tüm sisteme ve sırasıyla tüm bileşenlerine yönelik sayısal enerji dengesidir. Farklı sıcaklıklarda, istem bileşenlerinin geri çevrilmezlik oranı, ekserji verimliliği ve verimlilik sorunları her bileşen ve tüm tesis için incelenmiş bulunmaktadır. Bu çalışmada bir maddenin ekserji akışı termal, mekanik ve kimyasal enerji olarak sınıflandırılmıştır / ve entropi- üretimi akışı. 50050 kJ/kg lik düşük ısı değerine sahip yakıt doğal gazı yakıt olarak kullanılmıştır. Çevrim sıcaklıklarındaki dalgalanmaların tesisteki ekserjetik verimliliği ve ekserji tahribatını nasıl etkilediği soru üzerine odaklanılmıştır.

Türbindeki ekserji tahribatı oranı yaklaşık % 2.75 dir, bu oran yanma odasında ise yakalık % 55.77 dir. Sıcaklıktaki 8 C lik bir artışta, yanma odasının ekserji verimliliği % 49.83 olarak hesaplanmaktadır. Çalışmada elde edilen sonuçlara göre, yanma odası tesisteki geri çevrilmezliklerin en önde gelen araçlarından biridir. Aynı zamanda, ekserjetik verimlilik ve ekserji tahribatı türbinin giriş sıcaklığına göre önemli ölüde değişiklik göstermektedir. Bu sonuçlar temelinde, tesisin daha fonksiyonel hale getirilmesi yönünde tavsiyeler verilmektedir.

Anahtar sözcükler: Ekserjetik analiz, verimlilik: Geri çevrilmezlik, gaz türbini, performans

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TABLE OF CONTENTS

CHAPTERS:

LIST OF FIGURES

FIGURES

LIST OF TABLES

TABLES

LIST OF ABBREVIATIONS

SYMBOLS

$\dot{E}$	Rate of Exergy Flow (MW)
e	Specific Exergy (kJ/kg)
cp	Heat Capacity at Constant Pressure(kJ/kg K)
g	Acceleration due to Gravity (m/s2)
h	Specific Enthalpy (kJ/kg)
HHV	Higher heating Value (KJ/Kg)
ISO	International Standards Organization
LHV	Lower Heating Value (KJ/Kg)
$\dot{m}$	Mass Flow Rate (kg/s)
P	Pressure (bar)
$\dot{Q}$	Heat Transfer Rate (W)
R	Universal Constant (kJ/kg K)
r_p	Pressure Ratio
s	Specific Entropy [kJ/kg-K]
$\dot{S}$	Entropy Flow Rate(MW/K)
T	Temperature (K)
TIT	Turbine Inlet Temperature (K)
T_0	Ambient Temperature
x	Mole Fraction (Kmol)
$\dot{W}$	Power (kW)

SUBSCRIPTS

a	Actual
AC	Air Compressor
APH	Air Preheater
CC	Combustion Chamber
CV	Control Volume
D	Destruction
e	Outlet
f	Fuel
GT	Gas Turbine
i	inlet
o	Standard State

SUPERSCRIPTS

CHE	Chemical
P	Mechanical
PH	Physical Exergy
T	Thermal
W	Work

GREEK SYMBOLS

ε_D	Exergy Destruction Efficincy
ϵ	Effectivens
η	Exergy efficiency
η_{ov}	Overall Exergy Efficiency

CHAPTER 1

INTRODUCTION

1.1 Background

The active use of natural resources in all approaches of community has become more important, as well as technological progress and growth of population has increased the need for the best kind of energy sources. These sources availability is limited, as the renew ratio is unhurried which they are regarded non-renewable. Additionally, there is much discusses about the surroundings effects of the by-products produced by the use of these concentrated energy sources, but the main agreement has connected the fossil fuels prolific burning with the beginning of global climate alterations [1]. All of these elements have and will keep on to affect the price of high quality energy sources, so efficient using of resources such as, petroleum, coal and natural gas will be spirited for the near future. Presently the uses of fossil fuels consider one of the biggest use in sector of power generation. According to report published in 2014 that approximately 81% and 68% of the entire production of electricity in Iraq and worldwide comes from fossil fuel-based plants, conventional thermal [2]. With over two thirds of the electricity production worldwide derived from fossil fuels, effective resource utilization in this sector is critical. The using of gas turbine power plants become abroad and this leads the researchers to study and analysis its parts.

The method which used in order to analyze the processes of thermodynamic is the conception of exergy, or a substance's availability to do useful work. It can advance utilization of resource through identify wasteful, inefficient processes within systems of thermodynamic. Exergy is a great property of a substance as energy, but contrast in that in a process of given, it can be break down because of irreversibilities inherent to the process. While a First Law analysis may indicate that energy amount is conserved within process of given, it fails to determine the decrease in the energy quality, or the decrease availability of the substance to do work, in its final state. So it is useful to perform an analysis of exergy for the same process to identify the position, cause and magnitude of losses, so the chances to advance utilization of resource in the process are identified. This methodology can be useful to design of new systems or in analyzing existing systems to distinguish wasteful or inefficient processes and to identify ways to advance utilization of resource. The way for estimation performance of the Second Law for a typical gas turbine power system is exposed by Bejan et al [3] .Typical Second Law performance of different processes and using exergy methods to make economic Resolutions in design are drawing by Gaggioli [4]. Many researchers has accomplished the applying techniques of Second Law to definite processes like systems of gas turbine power plant.

1.2 Thesis Objectives

Design and analysis of thermal systems requires standards of many areas of mechanical engineering like, heat transfer, thermodynamics, fluid mechanics, mechanical design and manufacturing. This thesis deals with design of thermodynamics aspect. Advanced thermodynamic subjects have analyzed gas turbine power plant as one of thermal systems. These subjects consist of energy and exergy. Analysis of exergy that is combined of first and second laws of thermodynamic contribute to focus thermodynamics system inefficiencies. The study objective is to describe the system and its parts. In addition, analysis of thermodynamic using analyses of energy and exergy conducted of gas turbine based cycle. The First and Second Law of thermodynamics used for the different plant parts to define their performance and limit the quantities and exergy destruction positions in the open gas turbine. The gas turbine is most common figure of power generation technology in the worldwide. This is mainly correct in nations of oil producing like Iraq where liquid fuel or gas is freely available. In the study, the Najaf Power Plant, running a Bryton cycle is the case study being considered in this analysis.

1.3 Literature Survey

1.3.1 Energy and Exergy Studies

The whole energy is the amount of available energy plus unavailable energy. The energy flow in a system is consist of both available and unavailable energies. The meaning of energy simply is the entire energy of a system. While exergy is expression refers to available energy. Dincer and Rosen [5] explain the concept of both exergy and energy. They debates the fact that balance of energy does not supply information regarding the energy degradation or resources during a process. Nor does it quantify the quality or usefulness of the various forms of energy in the material streams flowing through a system that exists as products and wastes.

1.3.2 Exergy Analyses and Related Aspects

Exergy is depend on the first and second law of thermodynamics. Dincer and Rosen [5] confirm that analysis of exergy clearly refers to energy degradation positions in a process. The analysis results can lead to enhance operation and develop technologies. As well as, the analysis can measure the heat quality in a waste stream. Additionally exergy has defined by Hermann [6] as a method of estimation and comparing the reservoir of theoretically extractable work we termed resources of energy. Resources are regarded either matter or energy with properties that differ from the predominant conditions in the environment. The differences or alterations can be chemical, physical, or even nuclear exergy.

V. Tara Chand et al [7] studied the analysis of exergy is completed by conducting mass, energy and exergy balance of each part t in the gas turbine power plant in India. Analysis of Parametric of the various influence of factors Called compression ratio (rp), compressor inlet air temperature (AT) and turbine inlet temperature (TIT) on irreversibilites for every part of gas turbine plant is completed. Analysis of exergy reflect that combustion chamber is the higher sensitive part in gas turbine power plant. From the study can be concluded according to results that combustion chamber and gas turbine plant irrevesibilities increase and after that decrease with pressure ratio at last, Compressor inlet temperature has no advantage effect on components of gas turbine plant and combustion chamber and gas turbine plant Irreversibilities decrease with increasing of turbine inlet temperature.

Isam H. Aljundi [8], studied analysis of the energy and exergy of Al-Hussein power plant in Jordan that has capacity of 396 MW.This study are to analyze the parts of system individually and to identify and quantify the positions that have biggest energy and exergy wastes. Additionally, the influence of various reference environment state on the analysis will also be offered. The plant performance was evaluated by a componentwise modeling and an exhaustive break-up of energy and exergy wastes for the considered plant has been exposed. Main losses of energy happened in the condenser where 134MW is lost to the surrounding while only 13 MW was lost from the boiler system. The exergy destruction percentage ratio to the total exergy waste was discovered to be maximum in the boiler system (77%) followed by the turbine (13%), and then the enforced flow fan condenser (9%). additionally, the calculated thermal efficiency depend on fuel lower heating value which was 26% whereas the power cycle exergy efficiency was 25%. For a reasonable alteration in the reference environment state, no extreme alteration was seen in the main parts performance and the main conclusion stayed alike; in power plant the boiler considers the main resource of irreversibilities.. Chemical reaction is the most important resource of exergy waste in a boiler system that can be decrease by preheating the combustion air and decreasing the ratio of air–fuel.

Habib [9] presents an analysis of a cogeneration system. The irreversibilities quantifies analysis of the different parts for each plant. As well as, it presents the pressure of process on the thermal efficiency, the heat-to-power ratio effect and factor of utilization. The results explain that the entire irreversibility of the cogeneration plant is 38 percent lower compared to the common plant. This decreasing in the irreversibility is associated with an increase in the thermal efficiency and utilization factor by 25 and 24 percent, respectively. The results reflect that the destruction of exergy in the boiler is the highest.

Ganapathy et al. [10] perform an exergy analysis of a 50MW combined power plant located in India. They concluded that main exergy losses were occurs in the condenser. In this case, the energy could not be used elsewhere. They propose modifications in the combustor because huge loss in exergy. Horlock et al. [11]

perform analysis of exergy for three different fossil fuel based power plants. They also find that irreversibility's take place during combustion. Orhan et al. [12-18] argues analysis of exergy of different processes and parts of system. Sue et al. [19] also debate exergy analysis application for a gas combustion turbine based power generation system. Their results proved that analysis of exergy is a better exact evaluation efficiency of plant. As well as, destruction of exergy during decreases of combustion with the pressure ratio increase. In the work of Haseli et al. [20]. The analysis of thermodynamics of a combined gas turbine power plant with a solid oxide fuel cell is argued. The analysis results appear that increasing the temperature of compressor inlet decreases the efficiencies of energy and exergy for both the solid oxide fuel cell (SOFC) and conventional power plants. However, a gas turbine with SOFC has a 26.6% greater exergetic performance.

In a study performed by Bonnet et al. [21]. The coupling of an Ericsson engine, with a system involving natural gas combustion. In designing this plant, they used analyses of exergy, energy and exergo-economic. This study concentrate on the performance and design of a certain engine rather than a purely theoretical thermodynamic cycle. This enable sizes of heat exchanger with a balancing of performance of energy, the planning diagrams of Grassmann exergy, and the costs estimation of electrical and thermal energy production processes. Camdali et al [22] are applied Analyses of exergy and Energy to a dry system rotary burner with pre-calcinations in an important Turkish cement plant using actual data. The rotary burner consisted chemical and thermal processes. The first and second-law efficiencies are determined. In South Africa, analyses of exergy and energy of the destructions of energy in the industrial field are analyzed by Oladiran et al [23]. Tatiana et al. [24] also regards the analysis of exergy of a simply open gas turbine system. They show the studying important performance of the thermodynamic of a system part in purpose to discover which part of the system is the reason behind destruction of exergy and the possibility to avoid it.

Rosen [25] examined the thermodynamic performance of a water electrolysis for the purpose of producing hydrogen throughout using analyses of energy and exergy. Three cases are showed in which the principal driving energy inputs are (i) electricity, (ii) the high-temperature used to generate the electricity, and (iii) the heat source used to produce the high-temperature.

1.3.3 Exergy Efficiency

Horlock et al. [11] defined the rational efficiency of an open cycle. He clearly expressed relates to the ratio of the actual shaft work output from a power plant to the maximum work which could be gain in a process of reversible between prescribed inlet and outlet states. However, since different constraints may be applied to such an ideal reversible process, the maximum work obtainable would be variable. As a consequence so would the value of the rational efficiency.

Dincer and Rosen [25] distinguished efficiencies of energy and exergy and drawing the key factors of exergy efficiency. They affirm that efficiency of exergy frequently contribute exact understanding of performance than efficiency of energy. Energetic efficiency does not distinguished different energy forms, whether it is shaft work or a stream of low-temperature fluid. Also, efficiency of energy is more deals with decreasing of energy emissions to develop efficiency. In contrast, exergtic efficiency weights energy flows by accounting for each form of exergy present in the system. It concentrate on both external irreversibilities and internal irreversibilities in purpose of enhanced performance. In several cases, the irreversibilities are more important and more hardness to address, such that a judgment has to be made as to what is the product, what is counted as a loss and what is the input. Different resol arise about these lead us to various expressions of efficiency with the class. In order to decreasing materials and energy consuming, and to encourage the renewable resources using, Azouma et al. [26] evidence that conclusions depend on thermal efficiencies are not enough to reach to the best engine performance. Because of technical limitations (e.g. incomplete combustion), from the point of view the second law of thermodynamic, a exergy combination analysis and gas emissions analysis was essentially in the suggestion of a trade-off zone of engine load that could provide environmental interests and efficiency of engine. Though, exergetic efficiency does not concerns with quantity only but also with energy flows quality.

1.3.4 Chemical Exergy.

The chemical exergy analysis application is documented frequently by many researchers in the study of efficiencies of energy system. Analysis of exergy confirm its benefit in supplying exact observation to many energy systems efficiencies. Rivero et al. [27] examined the suggested model by Szargut for the calculation of the principles elements of chemical exergy, inorganic and organic substances. In Rivero's review of Szargut's model, he matches his reviewed values of principle chemical exergy with Szargut's values [27]. In Ertesvag,s work [28], the chemical exergy variants are examined for gaseous fuels and atmospheric gases with ambient temperatures between -30°C to 45°C, pressure from 0.6 bar to 1.1 bar and relative humidity from 10% to 100% throughout use Szargut's model.

The exergy analysis performed by Gaoet al. [29] on a coal-based polygeneration system for power and chemical production displays important development in energy savings when associated with separate systems. The analysis results point out that the combination of a power system with results of chemical process in 3.9% energy savings. Gao states that the "synthesis on the basis of thermal energy cascade utilization is the major addition to polygeneration performance advantage system" [29]. An important standard of a polygeneration system is the capacity ratio of the chemical process to the power system. This ratio has a big effect the corresponding of the both sides required in polygeneration system. Furthermore, besides the thermal energy integration, the cascade using of the chemical exergy is probable to be a key subject in extra studies of polygeneration systems.

The variations influence of in dead-state (a state that is in thermodynamic equilibrium with its surroundings) features on analyses of energy and exergy studied by Rosen et al. [30]. The research examined the effort of energy and exergy sensitivities values to the select of the dead-state property. Besides, it is also study the sensitivities of energy and exergy analyses results of complex systems and selection of dead-state feature. A case study of a coal-fired electrical generating station was hired in purpose of clarify the effect of dead state characteristics. However, it is revealed that the influence of dead-state features on values of energy and exergy is based on serious variation of the features. Furthermore, energy and exergy analyses results are typically insensitive to realistic differences in these features.

1.4 Organization of the Thesis

This thesis consists of five chapters. The whole necessary information for the purpose of identification on the main parts to power planet and analysis of exergy.

Chapter one, this chapter displays general overviews about studying of exergy analysis to different types of power plants and all related concepts.

Chapter two, it includes definition of gas turbine and its main parts. Also, studying of close and open cycle of gas turbine.

Chapter three, this chapter will introduce the concept of exergy and its relationship with energy and exergy. It also exposed how exergy could be an instrument to thermodynamic analysis. As well as the definition of Brayton cycle, deviation of actual gas turbine from idealized state and Brayton cycle with regeneration have been showed in this chapter.

Chapter four, this chapter gives a brief about Najaf city that contains Najaf power plant and description of SGT5-2000E gas turbine. Also necessary assumptions and governed equations to achieve analysis of exergy have been exposed in this chapter.

Chapter five, it contains results, discussions and conclusion.

CHAPTER 2

GAS TURBINE

2.1 Gas Turbine Technologies

Electric power generation gas turbines are industrial in two basic sizes, definitely, aero derivative turbines and industrial turbines. An industrial GT, frequently indicates to a single-shaft heavy-duty gas turbine. The industrial gas turbine power generating ability is characteristically ranged between 5 MW to at least 400 MW. Moreover the turbine is most likely operated with dual-fuel units using natural gas or distillate oil. Turbines of Aero-derivative (sometimes point to as medium GT's) are modified turbines of aircraft engine. They usually production within range of between 500 kW to at least 40 MW. This kind of gas turbine is most regularly run only with natural gas fuel. They most usually provide the needs of industrial markets [31]. These both kinds of gas turbines productions abilities are rated by the International Standards Organization (ISO). ISO specifies the following operating conditions:

- Conditions of Air inlet: air temperature 15^{0}C.
- Relative humidity 60%.
- Absolute pressure (sea-level) 101.325 kPa.

Such circumstances are experienced in Iraq specifically, in autumn and spring months. Aero-derivative and industrial gas turbine turbines schematic are exposed in Figure 1.

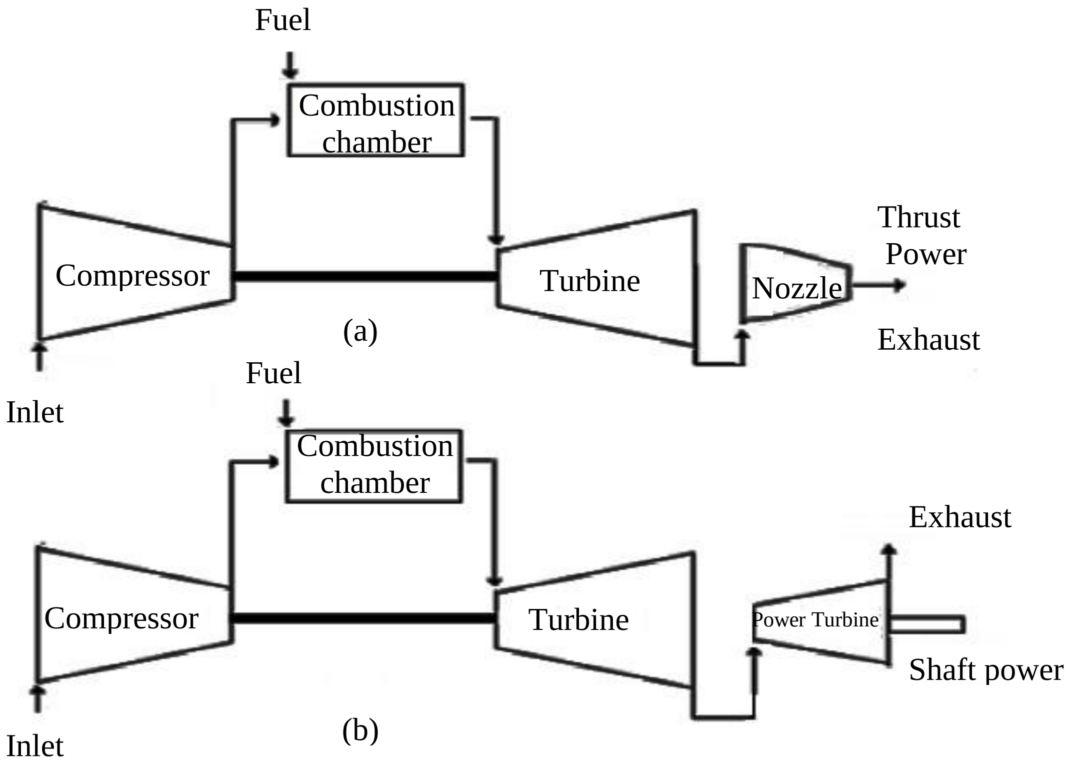


Figure 1 Schematic for (a) an Aircraft Jet Engine; and (b) a Land-Based Gas Turbine

Gas turbines such as the turbines which used at the Najaf Power Plant run in the open Brayton thermodynamic cycle. The Brayton cycle was suggested the first time by George Brayton for use in the engine of reciprocating oil-burning which he developed around 1870 [32]. In the present world, the turbine of Brayton cycle is used entirely for gas turbines where the processes of expansion and compression occur in rotating machinery.

The turbine system start with outside fresh air entering the gas turbine compressor stage. As the outside air enter through the compressor stage, the pressure is increased quickly. The compressed air is then enter into the combustor where fuel is injected into the high-pressure stream and ignited. The currently heated compressed air is freed into the turbine, where work is produced. The generate work is used to run the generator shaft generating electricity. A lesser portion of the work generate is also used to run the primary stage compressor. Generally, the hot mixture ($\sim 500^{o}$ C) leaves the turbine, it is enter through a heat-recovery generator. This is completed to recover some part of the lost heat, after that mixture of hot is left to the outside air

[33]. The system of heat recovery can be linked to a bottom cycle in systems of combined cycle or cogeneration.

Gas turbines are constant-volume systems. Shaft power output is almost proportional to the mass flow of combustion air at base load. At base load, the rate of mass flow of air amount into gas turbine identifies its production capacity. Also, the combustor increases power production through increasing fuel mass flow rate. Nevertheless, an increase in fuel mass flow rate is not proportional to power production. The general increase in production of power is smaller than is done by mass flow rate increase. Moreover, mass flow rate increase has opposite influence on the rates of heat (the ratio of fuel input rate to power produced). A flow occurred by increased mass flow rate which is moving very fast such some of injected fuel does not burned. In worst case scenario, liquid fuel which was injected into the flow is really burned outside of combustor. Anew designed gas turbine run at lesser air flow degrees per unit of power produced. The lesser flow degrees decline the cooling demand for inlet of gas turbine air-cooling technologies systems and so the net advantage increase. Capacity increases, though, might be limited through the extreme capacity of gas turbine, the rating of maximum generator kVA, or limitations of lubrication oil cooling.

The alteration between the ISO typical conditions of 15^0 C and the periods of hot summer peak of approximately 40^oC, may result in a 20% drop in gas turbine production. If, though, the inlet air flowing into gas turbine was cooled to 40^o C during these peak periods, a 27% increase would be completed. Reducing the inlet air temperature of gas turbine has some benefits related with the process [34]. A decrease in inlet air temperature has the possible to improve capacity, development heat amounts, increase efficiency of combustion turbine, extend life of turbine, and a postponed install addition gas turbine to treat with increasing demand.

A further element effecting gas turbine performance is relative humidity of the inlet outside air. The influence has been multiple and simulated researchers have tested and conducted in a controlled environment were relative humidity was being temperature and controlled was maintained constant at 15^oC. The test results display that the compressor needs additional energy to compress air of increasing humidity (higher density). Moreover, there is a decline in the generate work at the turbine. The total net influence is a decrease in the power production. Moreover, it is evidenced that a decline of 0.28 percentage points in the efficiency and of 2.7% in the electrical power production for an increase from 0% to 100% humidity (from totally dry to saturated air) [35].

2.2 Theory of Gas Turbine Components

2.2.1 Compressor

Effective compression of huge volumes of air is important for a successful engine of gas turbine. This could be accomplished in two compressors kinds, the axial-flow compressor and the centrifugal compressor. Most power plant compressors are axial-flow compressors because they are could be treated with huge rates of mass flow. The good compressor design aimed is to gain the maximum air a given diameter compressor with a least number of stages whereas maintain relatively high efficiencies and aerodynamic constancy over the operational range. Compressors contain a row of rotating blades followed by a row of stationary (stator) blades. A stage includes of a row of stator blades and a rotor row. The entire work accomplished on the working fluid is achieved by the rows of rotating, the stators exchanging the fluid kinetic energy to pressure and leading the fluid into the next rotor. The fluid go into with a primary speed relative to the blade and departing with a last relative speed at a different angle [36].

2.2.1.1 Centrifugal Air Compressor

The impeller that contains of huge number of blades, is attached on the shaft of compressor, within the stationary cover. As the impeller rotates, the pressure in area falls of suction and therefore the air go into during the eye and flows completely away from through blades of impeller. By way of a result speed and air increases pressure. Later this air go into and runs through the divergent routes molded by the diffuser blades. At this stage the air speed is declines but the pressure rises more. Someone can said that stage the kinetic energy is transformed into pressure energy. Lastly this high pressure air leaks from the compressor delivery portion. By this technique we able to gain ratios of high pressure by organizing the number of air compressor in successions [37]. The centrifugal compressor is exposed in Figure 2.

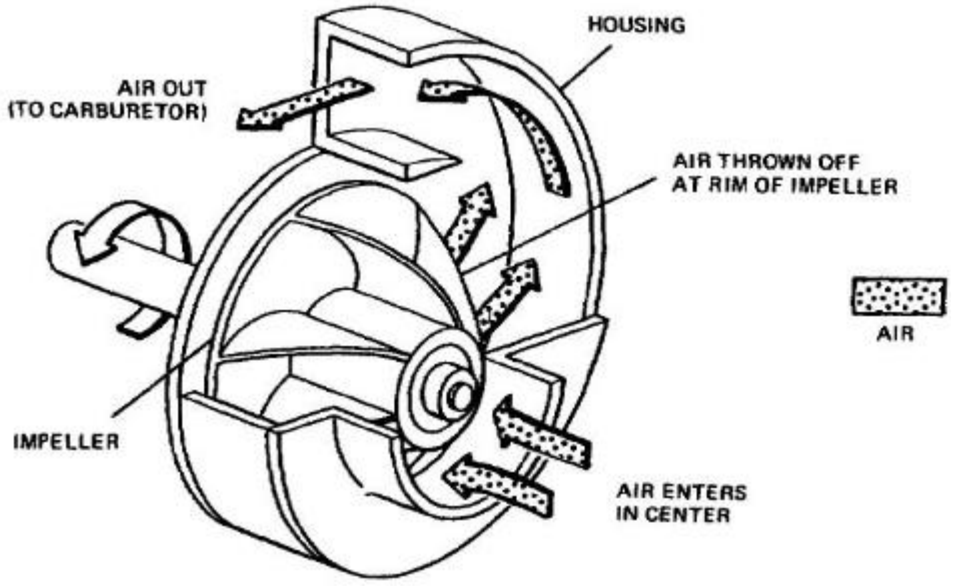


Figure 2 Centrifugal Air Compressor

2.2.1.2 Axial Air Compressor.

Such as kinds of compressors are frequently utilize presently. In axial compressor, the air flows in an axial direction right from suction to the liberation. The stator, which has stator blades, encloses the rotor that has been providing with blades of rotor. As well as the air go into from field of suction, it runs through the alternately organized stator and rotor blade rings. In flowing through every couple of blade rings molded up of one rotor blade ring and one stator blade ring, the air becomes compressed sequentially. Finally the air is arrived from area of delivery that is lesser in size match to side of suction. Axial flow compressors yield endless flow of compressed gas, and have high efficiencies advantages and great mass flow ability, particularly in relative to their cross-section. They do, however, involve some airfoils rows to complete big pressure increases making them complex and expensive relative to other schemes.

The Figure 3 displays a cross section of an axial compressor with various impellers. The gas flows axially alongside the compressor shaft from one impeller to another, directed by the stationary vanes. Each impeller/stationary vane traditional symbolizes one stage of compression. The fluid is speeded by impeller blades and afterwards it is slow down in the stator blades which then lead it into next stage of impeller blades

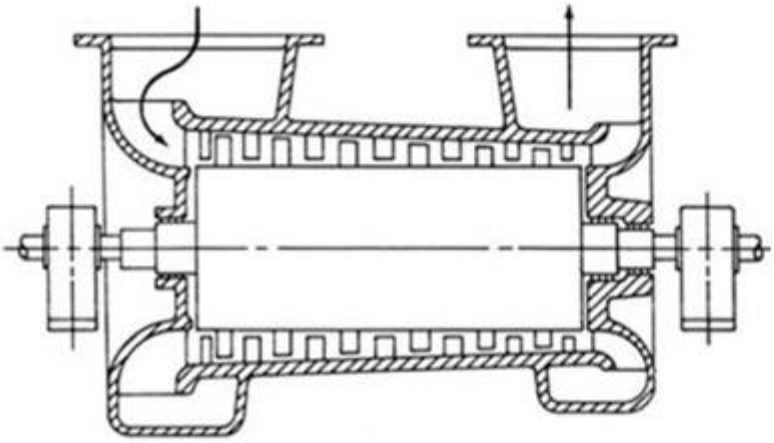


Figure 3 Axial Flow Compressor

Axial compressors are broadly utilize in gas turbines, such as high speed ship engines, jet engines and stations of small scale power. They are also utilize in manufacturing application like huge volume air separation plants, blast furnace air, propane dehydrogenation and fluid catalytic cracking air. Axial compressors, famous as superchargers, that have been utilize to enhancement the power of automotive reciprocating engines by compressing the intake air, though these are actual occasional.

2.3 Heat Exchanger

The gases departing temperature the turbine at the end of expansion is very high. Some of their heat content can be used to preheat the compressed air before it arrives the combustion chamber. This reheating is complete in counter-flow heat exchanger. With heat-exchanger, there is no alteration in the work of compressor, work of turbine and network complete. Nevertheless, there is substantial decrease in the fuel quantity and this aspect results in the increase in the thermal efficiency [38]. The arrangement of gas turbine employing heat exchanger is shown in Figure 6.

A regenerator efficiency is determine as:

$$\eta_{EX} = \frac{actual\ heat\ transfer}{maximum\ possible\ heat\ transfer\ from\ gases}$$

2.4 Combustion Chamber (Combustor)

Combustion is the chemical mixture of a substance with definite factors, frequently oxygen, accompanied by a high temperature production or heat transfer. The combustion chamber task is to receive the air from the compressor and to supply it to the turbine at the involved temperature, perfectly with no waste of pressure. Fundamentally, it is a direct-fired air heater in which fuel is flamed with less than one-third of the air after which the combustion products are then mixed with the remaining air. For the public open-cycle gas turbine, this wants the inner combustion of fuel. This means the problem of fuel operation, mixing and burning, must be addressed. Fuel is usually liquid or gaseous. Fuels liquid or gaseous are frequently hydrocarbons. Liquids may range from refined gasoline during kerosene and light diesel oil to a heavyweight remaining oil. Gases frequently being generally methane, natural gas, and butane. Combustion has a huge difficulties. The difficulty appears due to loss of pressure in combustion chamber. Nearly any fuel can be flamed effectively if enough pressure drop is available to supply the required turbulence for air and fuel mixing and if adequate volume is available to give the basic time for combustion to be achieved.

The gas turbine is a continuous flow system; therefore, the combustion in the gas turbine differs from the combustion in diesel engines. High rate of mass flow results in high velocities at various points throughout the cycle (300 m/sec). One of the vital problems associated with the design of gas turbine combustion system is to secure a steady and stable flame inside the combustion chamber. The gas turbine combustion system has to function under certain different operating conditions which are not usually met with the combustion systems of diesel engines. A few of them are listed below:-

1. Combustion in the gas turbine takes place in a continuous flow system and, therefore, the advantage of high pressure and restricted volume available in diesel engine is lost. The chemical reaction takes place relatively slowly thus requiring large residence time in the combustion chamber in order to achieve complete combustion.

2. The gas turbine requires about 100:1 air-fuel ratio by weight for the reasons mentioned earlier. But the air-fuel ratio required for the combustion in diesel engine is approximately 15:1. Therefore, it is impossible to ignite and maintain a continuous combustion with such weak mixture. It is necessary to provide rich mixture of ignition and continuous combustion, and therefore, it is necessary to allow required air in the combustion zone and the remaining air must be added after complete combustion to reduce the gas temperature before passing into the turbine.
3. A pilot or recirculated zone should be created in the main flow to establish a stable flame that helps to ignite the combustible mixture continuously.
4. A stable continuous flame can be maintained inside the combustion chamber when the stream velocity and fuel burning velocity are equal. Unfortunately most of the fuels have low burning velocities of the order of a few meters per second, therefore, flame stabilization is not possible unless some technique is employed to anchor the flame in the combustion chamber.

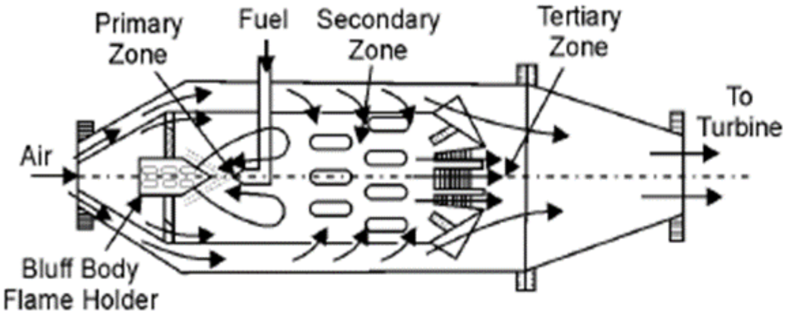


Figure 4 Combustion Chamber with Upstream Injection with Bluff-body Flame Holder

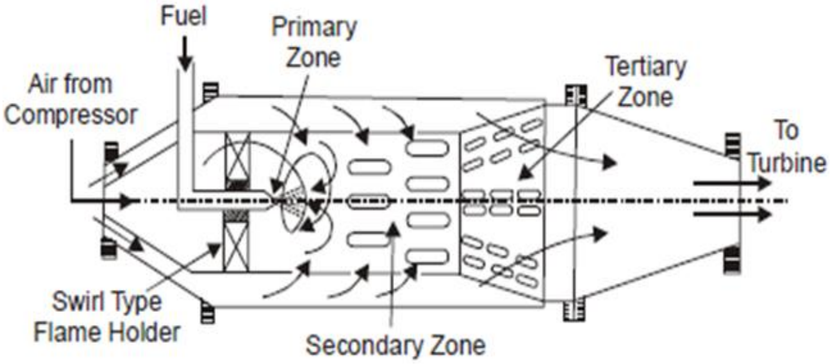


Figure 5 Combustion Chamber with Downstream Injection and Swirl Holder

The common methods of flame stabilization used in practice are bluff body method and swirl flow method. Two types of combustion chambers using bluff body and swirl for flame stabilization are shown in Figure 4 and Figure 5. The major difference between two is the use of different methods to create pilot zone for flame stabilization. Nearly 15 to 20% of the total air is passed around the jet of fuel providing rich mixture in the primary zone. This mixture burns continuously in the primary (pilot) zone and produces high temperature gases. About 30% of the total air is supplied in the secondary zone through the annuals around the flame tube to complete the combustion. The secondary air must be admitted at right points in the combustion chamber otherwise the cold injected air may chill the flame locally thereby reducing the rate of reaction. The secondary air helps to complete the combustion as well as helps to cool the flame tube. The remaining 50% air is mixed with burnt gases in the “tertiary zone” to cool the gases down to the temperature suited to the turbine blade materials. By inserting a bluff body in mainstream, a low-pressure zone is created downstream side that causes the reversal of flow along the axis of the combustion chamber to stabilize the flame. In case of swirl stabilization, the primary air is passed through the swirler, which produces a vortex motion creating a low-pressure zone along the axis of the chamber to cause the reversal of flow. Sufficient turbulence must be created in all three zones of combustion and uniform mixing of hot and cold bases to give uniform temperature gas stream at the outlet of the combustion chamber [39].

2.5 The Turbine

The gas turbine in its most public design is a heat engine working throughout a successions of processes. These processes includes of air compression taken from the atmosphere, gas temperature increasing by the constant-pressure combustion of fuel in the air, the hot gases expansion, and lastly, emptying of the gases to air, in a continuous flow procedure. It is alike to the Diesel and gasoline engines in its working medium and internal combustion, but is like the steam turbine in the steady flow of the working medium. The processes of compression and expansion are both achieved by means of rotating factors in which the energy transfer between fluid and rotor is influenced by kinetic action means, rather than by confident displacement as in reciprocating machinery [40]. Energy has been added to the gas stream in the combustor, where air is mixed with ignited and fuel. Combustion rises the gas flow velocity, temperature and volume. This is directed through a nozzle over the turbine's vanes, spinning the turbine and powering the compressor. Energy is mined in the form of shaft power, compressed air and insertion, in any combination, and utilize to power aircraft, generators, trains, ships and even tanks. Gas turbines traffic relatively huge air quantities through the cycle at very high speeds. Among the mechanical features of gas turbine engines are very smooth process and lack of vibration because of reciprocating action. The high rotational velocities used need very exact rotor balancing to prevent destructive vibration. Rotor components are greatly stressed with low safety factors. Vanes are very finely tuned to prevent resonant vibration. Gas turbines have relatively insufficient traffic (and no sliding) components and are not compel to vibratory forces. As a result, they are highly dependable when correctly shaped and advanced.

2.6 Open Cycle Gas Turbine

Gas turbines commonly run on an open cycle. Fresh air at ambient circumstances is drawn into the compressor, wherever its pressure and temperature 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 enlarge to the atmospheric pressure throughout nozzle vanes row. Expansion causes the turbine blade to wheel, which then moves a shaft. The shaft work thus generated drives the auxiliaries which contain generators, compressor etc. if electricity is to be produced. The exhaust gases depart the turbine in the open cycle are not re-circulated [41]. The open cycle gas turbine schematic chart is shown in Figure 6.

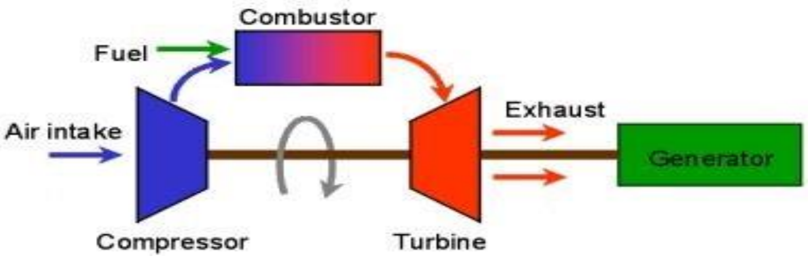


Figure 6 Open cycle gas turbine

2.7 Closed Cycle Gas Turbine

The open gas-turbine cycle can be designed as a closed cycle by using the air standard expectations. Here the process of expansion and compression stay alike, but process of constant-pressure heat-rejection to the outside air switches the process of combustion. The ideal cycle which the working fluid subjects in this closed loop is the Brayton cycle, which is taken of the processes of four internally reversible. Utilizing a closed cycle for the gas turbine advances the opportunity of utilizing a high pressure (and hence a high gas density) during the cycle, which would result in a decrease turbo-machinery size for a given production. The closed cycle gas turbine schematic diagram is exposed in Figure 7. The closed cycle unlock the opportunities of gases utilize other than air having more needed thermal features. The monatomic gas like helium which has the high value of definite heat could be utilize as working fluid. The best heat transfer features of helium means that the heat-exchanger and pre-cooler size can be about half that of units modeled for use with air [42].

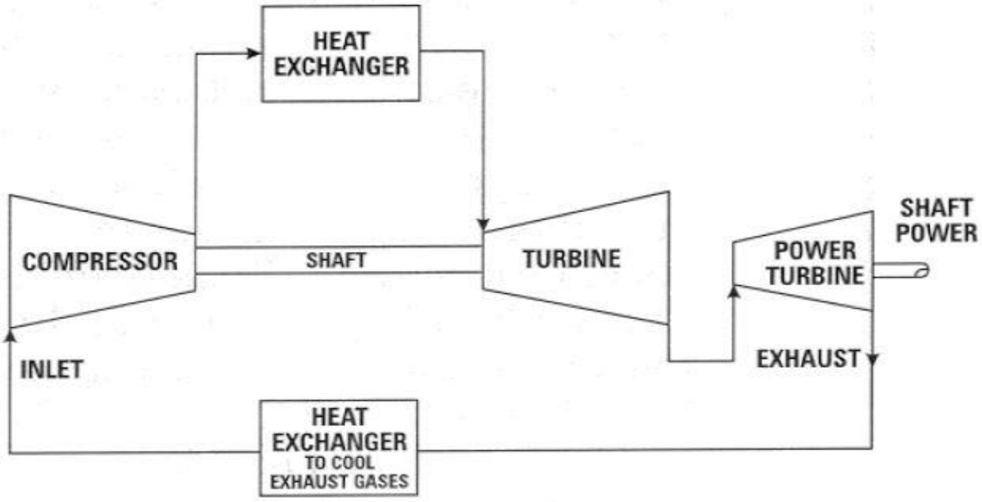


Figure 7 Closed Cycle Gas Turbine

2.8 Technologies of Gas Turbine Inlet Air-Cooling

System of A direct air conditioning was the first application of the combustion turbine inlet air-cooling model at unclear power plant in city Battle Creek, Michigan (USA) around the years 1987-88 [43]. Academically gas turbines able to achieved efficiencies as high as 65%. Nevertheless, most public simple open-cycle turbines only ever achieve an efficiency of approximately 40%. There are some increasing efficiency means like increasing inlet temperatures, reutilizing waste heat from gas turbine exhausts, decreasing internal losses, and the subject of this work, by reducing outside or compressor inlet temperatures [44].

To date, the temperatures of outside inlet air are usually decline or cooled by the way of the following methods:

- Moistened manner process of evaporative cooling.
- High-pressure vapor.
- Absorption chiller cooling.
- Refrigerate cooling process.
- Storage of Thermal energy.

The methods drawn above are between the most widely studied. These cooling techniques are achievement increasing application and popularity universally. [45] Evaluate the different gas turbines potential capacity increase f with inlet cooling. [46] Also contribute detailed debate on the subject of turbine inlet air cooling methods. The following subjects, practical experience using exclusive cooling techniques or hybrid combinations, economic and comparative studies are the researchers concerning in learning foundations and developments associations.

CHAPTER 3

EXEGY AND BRAYTON CYCLE

3.1 Energy, Entropy and Exergy

Thermodynamics is broadly viewed as the science of energy, and thermal engineering is concerned with making the best use of available energy resources. The thermodynamics is most descriptive of the early efforts to convert heat into power. Today the same name is broadly interpreted to include all aspects of energy and energy transformations, including power production, refrigeration, and relationships among the properties of matter.

The science of thermodynamics is built on two fundamental natural laws, known as the first and the second laws. The first law of thermodynamics is simply an expression of the conservation of energy principle. It asserts that energy is a thermodynamic property, and that during an interaction energy can change from one form to another but the total amount of energy remains constant. The second law of thermodynamics asserts that energy has quality as well as quantity, and actual processes occur in the direction of decreasing quality of energy. The high-temperature thermal energy is degraded as it is transferred to a lower temperature body. The attempts to quantify the quality or “work potential” of energy in the light of the second law of thermodynamics has resulted in the definition of the properties entropy and exergy.

The domains of energy, entropy and exergy are shown in Figure 8. The focus on the portion of the field of thermodynamics that intersects with the energy, entropy and exergy fields, and particularly emphasizes the intersection of all three domains [47]. Note that entropy and exergy are also used in other fields (such as statistics and information theory), and therefore they are not subsets of energy. Also, some forms of energy (such as shaft work) are entropy-free, and thus entropy subtends only part of the energy field. Likewise, exergy subtends only part of the energy field as well since some systems (such as air at atmospheric conditions) possess energy but no exergy. Most thermodynamic systems (such as steam in a power plant) possess energy, entropy, and exergy, and thus appear at the intersection of these three fields

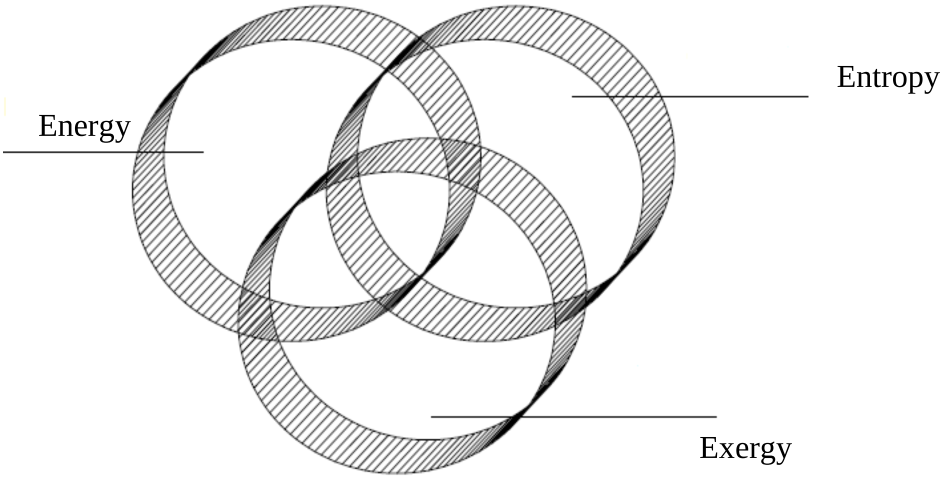


Figure 8 Interactions between the Domains of Energy, Entropy and Exergy

3.2 Concept of Energy.

The concept of energy was first introduced in mechanics by Newton when he hypothesized about kinetic and potential energies. However, the emergence of energy as a unifying concept in physics was not adopted until the middle of the 19th century and was considered one of the major scientific achievements in that century. The concept of energy is so familiar to us today that it is intuitively obvious, yet we have difficulty in defining it exactly. Energy is a scalar quantity that cannot be observed directly but can be recorded and evaluated by indirect measurements. The absolute value of energy of system is difficult to measure, whereas its energy change is rather easy to calculate. In our life the examples for energy are endless. The sun is the major source of the earth's energy. It emits a spectrum of energy that travels across space as electromagnetic radiation. Energy is also associated with the structure of matter and can be released by chemical and atomic reactions. Throughout history, the emergence of civilizations has been characterized by the discovery and effective application of energy to society's needs.

Energy manifests itself in many forms, which are either internal or transient, and energy can be converted from one form to another. In thermodynamic analysis, the forms of energy can be classified into two groups:-

- **The macroscopic:** Forms of energy are those where a system possesses as a whole with respect to some outside reference frame such as kinetic and potential energies.
- **The microscopic:** Forms of energy are those related to the molecular structure of a system and the degree of the molecular activity, and they are independent of outside reference frames. The sum of all the microscopic forms of energy is called the internal energy of a system [48].

3.3 The First Law of Thermodynamics (FLT)

The FLT stands for the first law of the conservation of energy. This is stated as energy can be neither created nor destroyed; it just changes form. The FLT defines internal energy as a state function and provides a formal statement of the conservation of energy. However, it provides no information about the direction in which processes can spontaneously occur, that is, the reversibility aspects of thermodynamic processes. For example, it cannot say how cells can perform work while existing in an isothermal environment. It gives no information about the inability of any thermodynamic process to convert heat into mechanical work with full efficiency, or any insight into why mixtures cannot spontaneously separate or unmixed themselves. An experimentally derived principle to characterize the availability of energy is required to do this. This is precisely the role of the second law of thermodynamics that we will explain later. The conservation of energy states that energy interaction at the system boundaries by matter flow, by heat and by work is equal to the change of the energy of the system [49].

For a steady state steady flow process, control volume energy rate balance may be

$$\dot{Q}_{C.V} + \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2} + g.Z_i \right) = \sum \dot{m}_e \left(h_e + \frac{V_e^2}{2} + g.Z_e \right) + \dot{W}_{C.V} \tag{1}$$

3.4 Second Law of Thermodynamics:

Some processes occurred spontaneously and some of them are not, for example the hot body has cooled spontaneously but the cool body has not heated absolutely. Gas has expanded from fraught space to empty one but the contrary does not happen. Chemical reactions going toward equilibrium and the inverse happen also. Generally all system going toward equilibrium and inverse of these processes need to external energy which means it should achieve work. The alterations in the internal energy or enthalpy do not regard indicators could depend on to refer the capability of reaction process. It does not refer to equilibrium then we need to a formula or law so we will take the second law to give us an explanation. The second law has two formula:

First formula (kelvin): It is impossible to do a periodic process through take a temperature from source and turn it to work without transfer temperature at the same time from hot source to cold one. For example vapor machine could not produce work without availability of high pressure and high temperature according to its environment. This formula related with equilibrium states if we released that it could gain work from system only, when the system does not actually reach to equilibrium state because of there is no process occur spontaneously and does not have what could be exploitation to get work.

The second formula (Clausius): It is impossible to transfer heat from cold source to hot one without transfer known amount of work to heat at the same time. This could be explain throughout working of electric refrigerator [50].

Entropy and another formula to second law of thermodynamic. It is from state variables to reversible processes set in system.

$$\Delta S \text{ rev} = 0$$

Increased in irreversible process

$$\Delta S \text{ irrev} = +$$

The entropy does not decrease of zero

$$\Delta S \neq -$$

Entropy function as mentioned is function state which depend on initially and finally state system therefore the alteration will be equal to

$$\Delta S = S2 - S1$$

For a steady state steady flow process, control volume entropy rate balance may be Written as

$$0 = \sum_j \frac{\dot{Q}_J}{T_j} + \sum_i \dot{m}_\iota \, . \dot{S}_i - \sum_e \dot{m}_e \, . \, \dot{S}_e + \dot{S}_{gen} \qquad (2)$$

3.5 Exergy

The limitation of energy recourses in the world lead a lot of countries to rethinking in their energy polices and put very strong norms to get rid of waste . As well as this subject makes the scientific community take a look at the energy switch and trying to find a new techniques to face challenges which represent by the limitation of energy recourses. The quantity of energy which related with the first law of thermodynamics affirms that energy cannot be created and destroyed. This law works as an important instrument for the measurement of energy during a process and help the engineer to come over the challenges. On the other hand, the quality of energy deals with the second law of thermodynamics. More specific this law interested with breakdown of energy during process, the entropy generation, and the lost opportunities to do work. As well as it suggests a lot of room improvement. The second law of thermodynamic has works as a very strong role in the encouragement of complex thermodynamic systems. The discussion starts with the introduction of exergy which means the maximum useful work which could be gained a system at given state and in definite environment and this discussion go on with reversible work which the maximum useful work that can be gained as system from a process between two specific state. Later on, the irreversibility has discussed which means the loss of work or the wasted work potential during process because of irreversibility [51].

3.6 Exergy as Tool of Thermodynamic Analysis

Analysis of exergy is instrument hired in the efficient power plants development. exergy is not a thermodynamic quantity; however it based on quantities of thermodynamic (i.e. entropy and enthalpy). Since its beginning in the early 60’s, the idea has been used during various components of the world [52]. The main target of analysis of exergy in applications of power plant is to detect and effectively reduce the irreversibility in every parts of the plant. To date, the exergy concept has been adopted by many researchers to huge collection of industrial processes.

Additional attractive exergy analysis aspect is that exergy is an active instrument used to complete the advance of energy efficient systems which have lesser environmental effects. Generally, analysis of exergy is appropriate to any system required work and heat transfer. Exergetic efficiency displays the real system effectiveness [53]. furthermore, the exergy due to the concentration variation of various types in most chemical fuels is smaller than the exergy of the required chemical bonds. Concentration exergy is determined as the relative multitude of a substance types compared with the average concentration of those types in the reference state. The concentration of uncounted molecules and atoms differ broadly across the world based on position. Thus, it is impossible to create an exact general determination of concentration exergy. Chemical exergy standard tables have been published for an extensive difference of types accounting for Gibbs free energy and an approximation of universal concentration exergy [54].

6.7 Exergy Components

In the absence of nuclear, magnetic, electrical, and surface tension effects, the total exergy of a system $\dot{E}$ can be divided into four components: physical exergy $\dot{E}^{\mathrm{PH}}$, kinetic exergy $\dot{E}^{\mathrm{KN}}$, potential exergy $\dot{E}^{\mathrm{PT}}$, and chemical exergy $\dot{E}^{\mathrm{CH}}$.

$$\dot{E} = \dot{E}^{\mathrm{PH}} + \dot{E}^{\mathrm{KN}} + \dot{E}^{\mathrm{PT}} + \dot{E}^{\mathrm{CH}} \tag{3}$$

Equation (2) can be expressed on unit-of-mass basis

$$\mathrm{e} = \mathrm{e}^{\mathrm{PH}} + \mathrm{e}^{\mathrm{KN}} + \mathrm{e}^{\mathrm{PT}} + \mathrm{e}^{\mathrm{CH}} \tag{4}$$

Kinetic exergy

$$\mathrm{e}^{\mathrm{KN}} = \frac{1}{2} \,.\, V^2 \tag{5}$$

Potential exergy

$$e^{PT} = g \cdot z \tag{6}$$

Physical flow exergy for simple compressible pure substances is given as

$$e^{PH} = (h - h_o) - T_o(S - S_o) \tag{7}$$

Exergy balance for steady-flow systems .Most control volumes encountered in practice such as turbines, compressors, nozzles, diffusers, heat exchangers, pipes, and ducts operate steadily, and thus they experience no changes in their mass, energy, entropy, and exergy contents as well as their volumes. The amount of exergy entering a steady flow system in all forms (heat, work, mass transfer) must be equal to the amount of exergy leaving plus the exergy destroyed. Then the rate form of the general exergy balance for a steady-flow process as

$$0 = \sum_j \left(1 - \frac{T_o}{T_j}\right) . \dot{Q}_j - \dot{W}_{CV} + \sum_i \dot{m}_i . e_i - \sum_e \dot{m} . e_e - \dot{E}_D \tag{8}$$

The last term in Equation (8), $\dot{E}_D$, is equal to $T_o . \dot{S}_{gen}$ from Guoy-Stodola theorem. Additionally, exergy losses are included in the fourth term of Equation (8).

3.8 Exergy vs Energy

The traditional method of assessing the energy disposition of an operation involving the physical or chemical processing of materials and products with accompanying transfer and/or transformation of energy is by the completion of an energy balance. This balance is apparently based on the FLT. In this balance, information on the system is employed to attempt to reduce heat losses or enhance heat recovery. However, from such a balance no information is available on the degradation of energy, occurring in the process and to quantify the usefulness or quality of the heat content in various streams leaving the process as products, wastes, or coolants.

The exergy method of analysis overcomes the limitations of the FLT. The concept of exergy is based on both FLT and SLT. Exergy analysis can clearly indicate the locations of energy degradation in a process that may lead to improved operation or technology. It can also quantify the quality of heat in a reject stream. So, the main aim of exergy analysis is to identify the causes and to calculate the true magnitudes of exergy losses. Table 1 presents a general comparison of both energy and exergy.

Energy	Exergy
Is dependent on the parameters of matter or energy flow only, and independent of the environment parameters.	is dependent both on the parameters of matter or energy flow and on the environment parameters.
Has the values different from zero (Equal to mc^2 upon Einstein's equation)	is equal to zero (in dead state by equilibrium with the environment).
is governed by the FLT for all the processes.	is governed by the FLT for reversible processes only (in irreversible processes it is destroyed partly or completely).
Is limited by the SLT for all processes (incl. reversible ones).	is not limited for reversible processes due to the SLT.
Is motion or ability to produce motion.	is work or ability to produce work.
is always conserved in a process, so can neither be destroyed or produced.	is always conserved in a reversible process, but is always consumed in an irreversible process.
is a measure of quantity only.	is a measure of quantity and quality due to entropy

Table 1 Comparison of Energy and Exergy

To begin with, we must distinguish between exergy and energy in order to avoid any confusion with the traditional energy-based methods of thermal system analysis and design. Energy flows into and out of a system via mass flow, heat transfer, and work (e.g., shafts, piston rods). Energy is conserved, not destroyed: this is the statement made by the FLT. Exergy is an entirely different concept. It represents quantitatively the "useful" energy, or the ability to do work-the work content-of the great variety of streams (mass, heat, work) that flow through the system. The first attribute of the property "exergy" is that it makes it possible to compare on a common basis interactions (inputs, outputs) that are quite different in a physical sense. Another benefit is that by accounting for all the exergy streams of the system it is possible to determine the extent to which the system destroys exergy. The destroyed exergy is proportional to the generated entropy. In actual systems, exergy is always destroyed, partially or totally: this is the statement made by the SLT. The destroyed exergy, or the generated entropy is responsible for the less-than-theoretical efficiency of the system [55].

3.9 Brayton Cycle

Gas-turbines usually operate on an open cycle shown on the Figure 9. A compressor takes in fresh ambient air (state 1), compresses it to a higher temperature and pressure (state2).Fuel and the higher pressure air from compressor are sent to a combustion chamber, where fuel is burned at constant pressure. The resulting high temperature gases are sent to a turbine (state 3). The high temperature gases expand to the ambient pressure (state4) in the turbine and produce power. The exhaust gases leave the turbine. Part of the work generated by the turbine is sent to drive the compressor. The fraction of the turbine work used to drive the compressor is called the back work ratio [56].

Since fresh air enters the compressor at the beginning and exhaust are thrown out at the end, this cycle is an open cycle. By utilizing the air-standard assumptions, replacing the combustion process by a constant pressure heat addition process, and replacing the exhaust discharging process by a constant pressure heat rejection process, the open cycle described above can be modeled as a closed cycle, called ideal Brayton cycle. The ideal Brayton cycle is made up of four internally reversible processes.

- 1-2 isentropic compression (in a compressor).
- 2-3 constant pressure heat addition.
- 3-4 isentropic expansion (in a turbine).
- 4-1 constant pressure heat rejection.

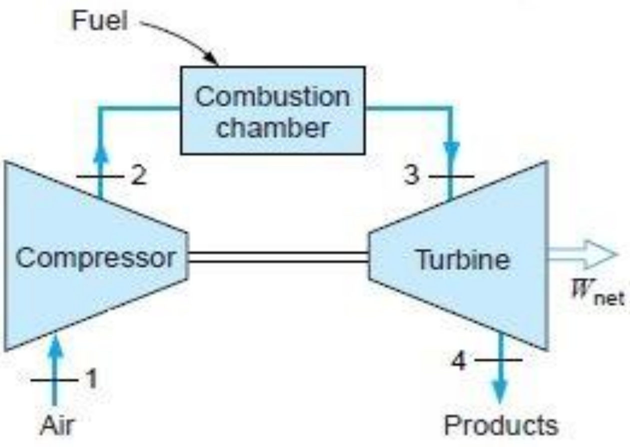


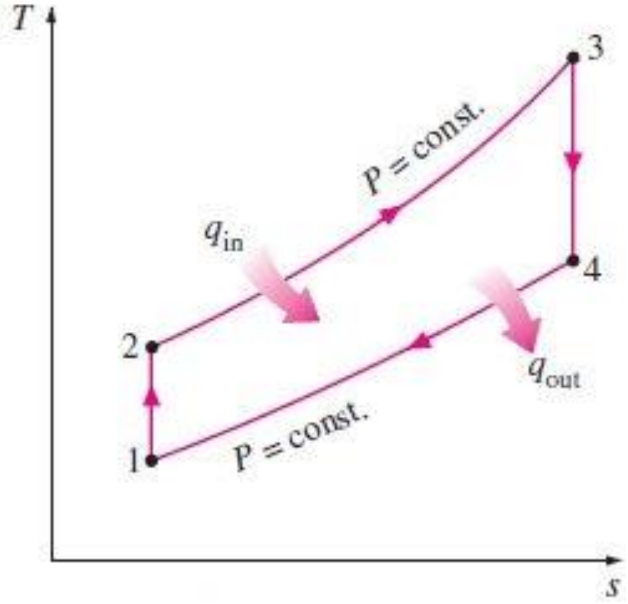
Figure 9 an Open Cycle Gas Turbin

- **Air-standard assumptions**: Assumptions that the processes of compression and expansion are adiabatic (insulated) and reversible (isentropic), that there is no pressure drop through the process of heat addition, and that the pressure departure the turbine is equivalent the pressure entering the compressor
- **Internally reversible processes:** States of Thermodynamics which, for given temperature restrictions, a wholly reversible cycle has the maximum probable efficiency and specific work production, reversibility being both thermal and mechanical. Mechanical reversibility is states sequence in mechanical equilibrium, i.e. fluid motion without turbulence, friction, or free expansion. Thermal reversibility is a results of the Second Law of thermodynamics, which states that heat have to be added only at the extreme temperature of the cycle and rejected at the lowest temperature.
- **Isentropic**: Processes being completed reversibly and adiabatically.

3.9.1 Mathematical Treatment of Brayton Cycle

The T-S and P-V diagrams of an ideal Brayton cycle are shown in Figue 10 and Figure 11 correspondingly. Brayton cycle four processes are accomplished in steady flow devices so they must be studied as processes of steady-flow. When the alterations in kinetic and potential energies are ignored, the energy balance for a steady-flow process can be express, on a unit-mass basis, as

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = (h_{out} - h_{in}) \tag{9}$$



Figuer 10 T-S Diagram of Brayton Cycle

Thus, heat transfers to and from the working fluid are

$$q_{in} = h_3 - h_2 = C_p (T_3 - T_2) \tag{10}$$

$$q_{out} = h_4 - h_1 = C_p (T_4 - T_1) \tag{11}$$

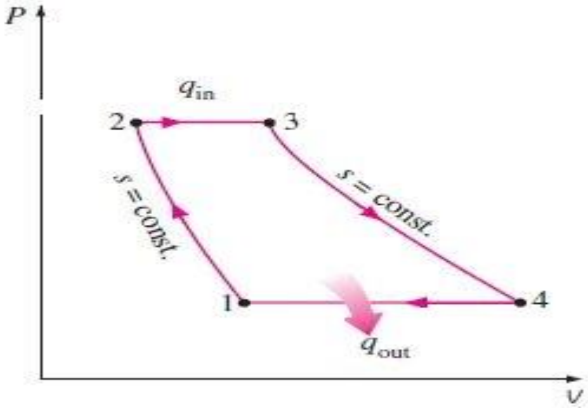


Figure 11 P-V Diagram of Brayton Cycle

Then the thermal efficiency of the ideal Brayton cycle under the air-standard assumptions becomes

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{C_p(T_3 - T_2)}{C_p(T_4 - T_1)} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)} \tag{12}$$

Processes 1-2 and 3-4 are isentropic ,and $p_2 = p_3$ *and* $p_4 = p_1$. Thus

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = \left(\frac{p_3}{p_4}\right)^{\frac{k-1}{k}} = \frac{T_3}{T_4} \tag{13}$$

Replacing these equations into relation of the thermal efficiency and simplifying give the thermal efficiency as

$$\eta_{th} = 1 - \frac{1}{\left(r_p\right)^{\frac{k-1}{k}}} \tag{14}$$

Where

$$r_p = \frac{p_2}{p_1} \tag{15}$$

Is the pressure ratio and k is the definite heat ratio. Under assumptions of the cold-air, of an ideal Brayton cycle thermal efficiency based on the gas turbine pressure ratio and the definite heat ratio of the working fluid (if different from air). The thermal efficiency rises with both of these parameters, which is also the case for actual gas turbines [57].

3.9.2 Deviation of Actual Gas Turbine Cycle from Idealized Stste

The actual gas turbine cycle contrast with the ideal Brayton cycle. Some pressure waste through the heat addition and processes of rejection cannot be avoid. The actual work input to the compressor will be more, and the actual work output from the turbine will be less because of irreversibility's. [58] The deviation of actual compressor and turbine manner from the idealized isentropic behavior can be exactly accounted for by using the adiabatic efficiencies of the turbine and compressor defined as

$$\eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}} \tag{16}$$

$$\eta_C = \frac{w_s}{w_a} = \frac{h_1 - h_{2s}}{h_1 - h_{2a}} \tag{17}$$

Where states 2a and 4a are the actual exit states of the compressor and the turbine, respectively, and 2s and 4s are the corresponding states for the isentropic case, as illustrated in Figure 12.

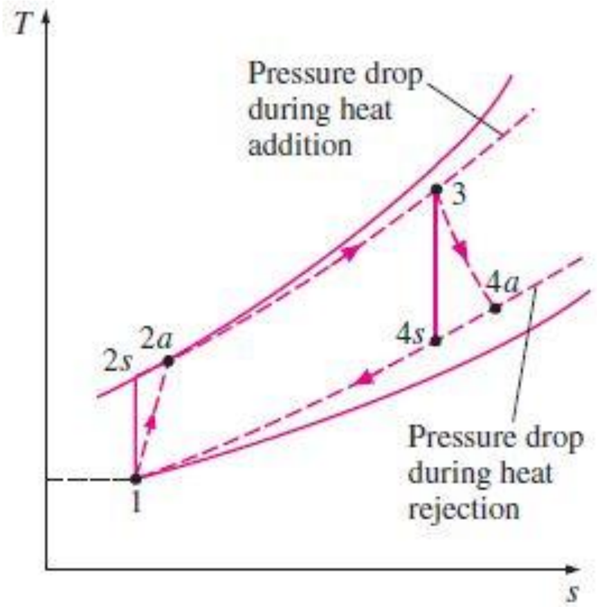


Figure12 The Deviation of an Actual Gas-Turbine Cycle From the Ideal Brayton Cycle as a Result of Irreversibilities

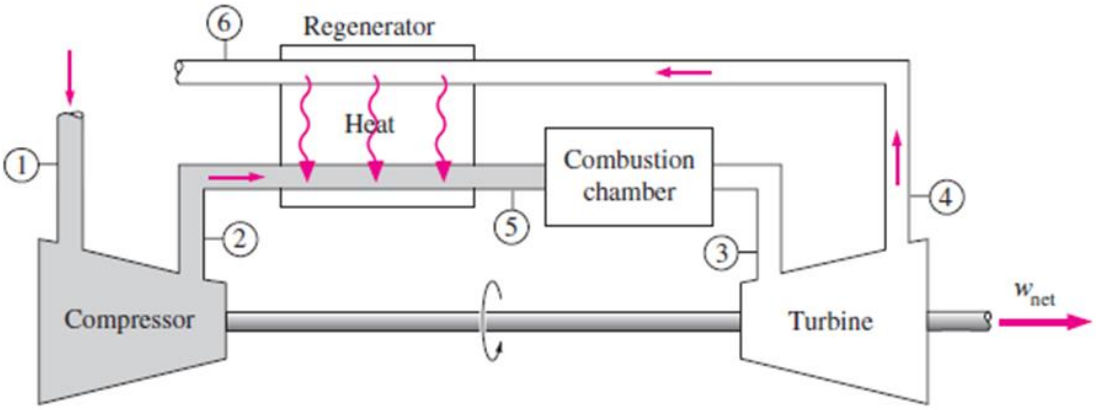
3.9.3 The Brayton Cycle with Regeneration

In gas-turbine engines, the temperature of the exhaust gas leaving the turbine is often considerably higher than the temperature of the air leaving the compressor. Therefore, the high-pressure air leaving the compressor can be heated by transferring heat to it from the hot exhaust gases in a counter-flow heat exchanger, which is also known as a regenerator or a recuperator as shown in Figure 13. The thermal efficiency of the Brayton cycle increases as a result of regeneration since the portion of energy of the exhaust gases that is normally rejected to the surroundings is now used to preheat the air entering the combustion chamber. This in turn, decreases the heat input (thus fuel) requirements for the same network output. Note, however, that the use of a regenerator is recommended only when the turbine exhaust temperature is higher than the compressor exit temperature. Otherwise, heat will flow in the reverse direction (to the exhaust gases), decreasing the efficiency. This situation is encountered in gas-turbine engines operating at very high pressure ratios [59]. The highest temperature occurring within the regenerator is T4 as shown in Figure 14. The temperature of the exhaust gases leaving the turbine and entering the regenerator. Under no conditions can the air be preheated in the regenerator to a temperature above this value. Air normally leaves the regenerator at a lower temperature, T5. In the limiting (ideal) case, the air exits the regenerator at the inlet temperature of the exhaust gases T4. Assuming the regenerator to be well insulated and any changes in kinetic and potential energies to be negligible, the actual and maximum heat transfers from the exhaust gases to the air can be expressed as

$$q_{regene.act} = h_5 - h_2 \tag{18}$$

And

$$q_{regen.max} = h_5 - h_2 = h_4 - h_2 \tag{19}$$



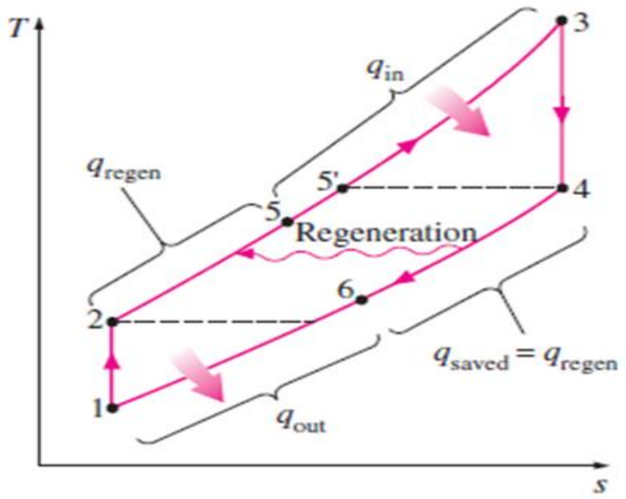
Figuer 13 A Gas-Turbine Engine with Regenerator

The extent to which a regenerator approaches an ideal regenerator is called the effectiveness ` and is defined as

$$\epsilon = \frac{q_{regen.act}}{q_{regen.max}} = \frac{h_5 - h_2}{h_4 - h_2} \tag{20}$$

When the cold-air-standard assumptions are utilized, it reduces to

$$\epsilon \cong \frac{T_5 - T_2}{T_4 - T_2} \tag{21}$$



Figuer 14 T-S Diagram of a Brayton Cycle with Regeneration.

A regenerator with a higher effectiveness obviously saves a greater amount of fuel since it preheats the air to a higher temperature prior to combustion. However, achieving a higher effectiveness requires the use of a larger regenerator, which carries a higher price tag and causes a larger pressure drop. Therefore, the use of a regenerator with a very high effectiveness cannot be justified economically unless the savings from the fuel costs exceed the additional expenses involved. The effectiveness of most regenerators used in practice is below 0.85.

CHAPTER 4

GAS TURBINE SGT5- 2000E POWER PLANT IN IRAQ AL NAJAF

4.1 Introduction

This chapter is intended to depict an overall plant, describes the functional operation of a gas turbine, and introduces major turbine components in the turbine gas path from inlet to exhaust. The gas path is defined as the path gases flow through the gas turbine starting at the air inlet, into the compressor, then through the combustion chambers, into the turbine, heat exchanger, and finally through the exhaust to the atmosphere. There in the ALNajaf city two gas turbine power plant AL Najaf power plant and Al Hadareya. Al Najaf power plant consists of 5 SGT5-2000E gas turbine units that have a generation capacity 151.74 MW. The total installed generating capacity of plant is about 758.7 MW. However, this study covers only one gas turbine because all of them are similar Siemens company manufacture.

4.2 AL Najaf City

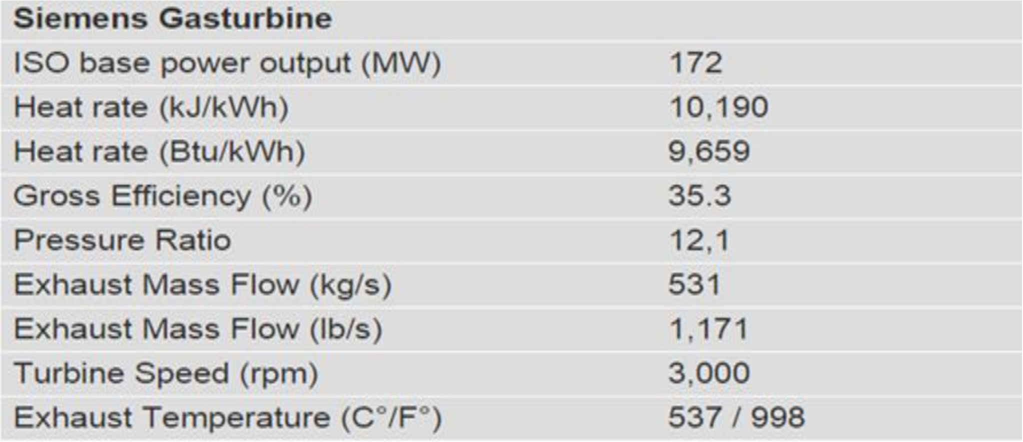
Najaf province considers one of the middle Euphrates and Iraqi eighteen provinces. Its center is Najaf city which characterize with religious nature. This city According to Twelver Shia represent holy city and gate of sciences for Shiites. It contains Imam Ail tomb, scientific Hawza and The religious authority. It is one of Iraq southern provinces which lies on the edge of western plateau of Iraq, South west of the capital Baghdad and away from it about 161km. it rises 70m above sea level. It bordered from north and north-east with Karbala city which away from Najaf about 80km. Also low of Najaf Sea bordered the city from south and west. Najaf today is Najaf of Kufa (to distinguish from Najaf of Hirah). It was summer resort for Lakhmids (kings of Hirah), there were Christian monasteries before Islamic conquest. The town turn to a city, expanded and crowded population because of the presence of Imam Ail tomb which gave the city respect character. It becomes religious authority center and destination of scholars. Najaf is an Arabic name which means a place cannot surmounted with water. The poets Mohammed Mehdi Algwahrey and Mustafa Jamal al-din represent the most famous figures in Najaf in our present time. Saddar educational hospital and Middle Euphrates hospital are the most important hospitals in the city. Najaf city contains two power planets which are Najaf power planet 758.7MW. Figure 15 shows Satellite Image of Al Najaf power plant. Alhideray gas power planet 162MW which lies on Alhideray Township.

Figure 15 Satellite Image of Al Najaf Power Plant

4.3 Description of SGT5-2000E Gas Turbine

The Siemens SGT5-2000E gas turbine is a stationary gas turbine. The SGT5-2000E is rated to provide more than 172 MW at ISO conditions. The SGT5-2000E gas turbine is an extremely well-proven, powerful engine for the 50-Hz for use in simple cycle or combined cycle processes with or without combined heat and power. It is suitable for all load ranges, especially also for the peak load range. For integrated coal gasification combined cycle applications. Besides the application in power plants, the SGT5-2000E can also be used for various other applications in the oil and gas industry. The compressor drive design, derived from proven standards, can be used for the production of liquefied natural gas (LNG) – either as a direct mechanical compressor drive or as an all-electric generator version. The SGT5-2000E has a proven record for toughness and strength with more than 380 units in operation and an accumulated total of over 16 million operating hours. also it features Combustion chambers lined with individually replaceable ceramic tiles,16-stage axial-flow compressor with variable-pitch inlet guide vanes, Four-stage turbine and Hybrid burners for premix and diffusion mode operation with natural gas, fuel oil and special fuels such as heavy oil and refinery residues [60].

4.4 SGT5-2000E Technical Data Design



Siemens Gasturbine	
ISO base power output (MW)	172
Heat rate (kJ/kWh)	10,190
Heat rate (Btu/kWh)	9,659
Gross Efficiency (%)	35.3
Pressure Ratio	12,1
Exhaust Mass Flow (kg/s)	531
Exhaust Mass Flow (lb/s)	1,171
Turbine Speed (rpm)	3,000
Exhaust Temperature (C°/F°)	537 / 998

Gas Turbine Physical Dimensions	
Approx. Weight (kg/lb)	216,000 / 476,000
Length (m/ft)	14.0 / 46
Width (m/ft)	12,5 / 41
Height (m/ft)	8,5 / 28

4.5 Description of AL Najaf Gas Turbine Power Plant

Figure 16 gives the overview of the structure, working, exergy flows and the assumptions for analysis of a 115.74-MW gas turbine system. The components of the system include an air-compressor (AC), a combustion chamber (CC), and a gas turbine (GT). Air enter to the compressor at 25°C has a mass flow rate of 496.0 kg/s. 25°C and 1.0135 bar is the temperature and pressure of the air input, respectively.

The compressor has isentropic efficiency of 83% and amplifies the pressure up to 8.5 bar. The turbine has the inlet temperature of 1046°C and an isentropic efficiency of 88%. According to Figure 16, the efficiency of the air pre-heater heat exchanger is 75%. The pressure of the hot gas exhaust from the air pre-heater is 1.034bar. The flow streams through both the air pre-heater and the combustion chamber experiences a pressure drop of 3% of the inlet pressure. At a temperature of 25°C and pressure of 30.0 bar, the fuel (fuel Natural gas 10.5 Kg/s) is introduced

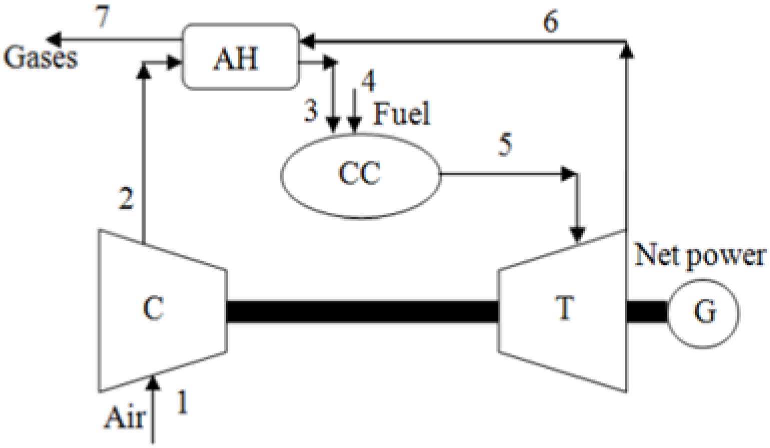


Figure 16 Gas Turbine System

4.6 Data of Operation power Plant

Data used for this study were collected from the power plant’s log book and Final Report such as average daily power generated, mass flow rate, pressure and temperature. Working fluid parameters (air and fuel specific capacities and universal constants) were obtained from appropriate thermodynamic tables as shown in the table 2 below.

State	Mass flow rate (Kg/s)	Temperature (K)	Pressure (bar)
1	496.000	298.15	1.0135
2	496.000	602.00	8.6100
3	496.000	795.90	8.266
4	10.5000	298.15	30.000
5	506.500	1319.0	8.020
6	506.500	860.50	1.074
7	506.500	694.20	1.034

Table 2: Data for Gas Turbine Power Plant Mass Flow rate, Temperature (25ºC), and Pressure (1.135 bar)

4.7 Ambient Temperature

Efficiency and electric-power output of gas turbines vary according to the ambient conditions (ambient temperature). The amount of these variations greatly affects electricity production, fuel consumption and plant incomes. At the same time, the amount of performance variation with the ambient conditions also depends on the gas turbines design parameters. When other parameters held constant, the performance of plant are strongly depends only on ambient temperature (AAT). Main parameters of plant influenced by ambient temperature as in equations below based on figure 16.

- Mass flow rate of air (m_a) at inlet of compressor: $m_a = \frac{P_1V_1}{RT_1}$, When P_1, V_1 & R are held constant, then m_a is inversely proportional to AAT (T_1).
- Outlet temperature of compressor (T_2): $T_2 = T_1\left[1 + \frac{(r_p)\left(1-\frac{1}{k}\right)-1}{\eta_c}\right]$ When r_p, k & η_c are held constant, then T_2 is directly proportional to T_1.
- Compression Work (W_C):$W_c = \frac{P_1V_1}{R} . C_p . \left[\left[1 + \frac{(r_p)\left(1-\frac{1}{k}-1\right)}{\eta_c}\right] - 1\right]$ When P_1, V_1, R, r_p, k, C_p & η_c are constant, W_C is independent of T_1. There is no effect of T_1 on the compressor work.

- Mass flow rate of fuel to GT-CC: $m_f = \frac{P_1\, V_1}{RT_1} \cdot \left[\frac{C_{pg}.T_5 - C_{pa}\, T_1\, .\frac{\left(1 + (r_p)\left(1 - \frac{1}{k}\right) - 1\right)}{\eta_c}}{HHV.\eta_c - C_{pg}\,.T_3} \right]$

  When P_1, V_1, R, r_p, k, η_C, , C_{pa}, C_{pg} & T_3 are held constant, m_f is inversely proportional to T_1.

- Outlet temperature of gas turbine (T_6): $T_6 = T_5 \left[1 - \eta_{GT} \left[1 - \left(\frac{1}{r_p} \right)^{\left(1 - \frac{1}{k}\right)} \right] \right]$,

  When all parameters like T_5, R, r_p, k & η_{GT} are constant, T6 is independent of T_1.

- Gas Turbine Work (W_{GT}): When P_1, V_1, R, r_p, k,η_c ,C_{pa}, C_{pg}, T_5 & T_6 are held constant, W_{GT} is inversely proportional to T_1.
- Net Power Output Gas Turbine Plant at Generator shaft: $W_{NGT} = (W_{GT} - W_C)$. When W_C, is held constant, W_{GT} is inversely proportional to T_1.
- Gas Turbine Plant Efficiency: When P_1, V_1, R, C_{pa}, C_{pg}, η_c, η_{GT}, and T_5 are constant except T_1. The net power output of GT plant is inversely proportional to T_1 and energy supplied to GT plant is also inversely proportional to T_1. Therefore efficiency of GT plant is inversely proportional to T_1

  Therefore, in order to determine the actual performance variation with the ambient conditions, gas turbine design parameters and ambient conditions of the installed place should be known.

4.8 Turbine Inlet Temperature (TIT)

The turbine inlet temperature (TIT) is an important parameter for gas turbines. The efficiency, power output and pressure ratio are increased with increasing turbine inlet temperature (highest temperature in cycle T5= TIT). It is clear from the following equations.

$$\eta_{th} = 1 - \frac{1}{(r_p)^{\frac{k-1}{k}}} \quad , \quad W_{GT} = (m_a \,.\, m_f) \,.\, C_{p\,gas} \,.\, (T_5 - T_6),$$

$$\dot{W}_{Net} = \dot{W}_{GT} - \dot{W}_{AC} \quad , \quad \eta_{plant} = \frac{\dot{W}_{Net}}{\dot{E}^{CHE}}$$

The current trend for gas turbine development is that the further increase of TIT and the reduction of losses related to it are focused very strongly by the gas turbine manufacturers

4.9 Assumption

This section is intended to detail the analysis of the components system. The subsystems are dealt with in some detail in the following subsections. During exergy analyses, the following assumptions were made:

- Steady state operation for all components.
- Compressor and turbine are adiabatic and, hence, no heat transfer occurs between them and the surroundings.
- All kinetic and potential exergetic terms are negligible.
- The chemical exergetic term does not change in the turbine, pumps, compressor or the heat exchanger.
- The combination of a compressor and turbine as a turbocharger is used in this system. Therefore, a fraction of power produced by the turbine is used in the compressor and the rest is a useful power output.
- Air is an ideal gas with a composition of 21 % oxygen and 79 % nitrogen.
- Isentropic operation is assumed for the compressor and the turbine.

4.10 Overview of Analysis

For this study, standard atmospheric conditions at AL Najaf power plant represent the environment. The total exergy of a system is comprised of four main components defined as the physical, chemical, kinetic and potential exergies. In this study, the kinetic and potential exergy components are assumed to be negligible. The physical exergy represents the maximum theoretical work that can be obtained as a system goes from a state at temperature T and pressure P to the restricted dead state, or state at which the system and environment are in mechanical and thermal equilibrium, at the reference temperature T_o and P_o. Steady state control volume balance equations were used for the analysis. The steady state continuity equation and first law energy equations were used to calculate the mass flow and energy transfer rates across the boundaries of the control volumes. Steady State Continuity Equation.

$$\sum \dot{M}_i = \sum \dot{M}_e \tag{22}$$

Steady state Energy Balance Equation

$$\dot{Q}_{CV} - \dot{W}_{CV} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \tag{23}$$

A general exergy balance equation, applicable to any component of a thermal system can be formulated by utilizing the First and Second Laws of Thermodynamics. The thermo – mechanical exergy (physical exergy) flow may can be divided into its thermal and mechanical components [61].

$$\dot{E}_i^{ph} - \dot{E}_e^{ph} = (\dot{E}_i^T - \dot{E}_e^T) + (\dot{E}_i^P - \dot{E}_e^P) \tag{24}$$

Where the subscripts i and e denote, respectively, exergy flow streams entering or leaving the plant component.

The thermal and mechanical components of the exergy stream for an ideal gas with constant specific heat capacity may be written as

$$\dot{E}^T = \dot{m}\ C_P \left[(T - T_o) - T_o \ln\frac{T}{T_o}\right] \tag{25}$$

$$\dot{E}^P = \dot{m} R T_o \ln\frac{P}{P_o} \tag{26}$$

The entropy for each state is given by

$$\dot{S} = \dot{m} \left(C_P \ln\frac{T}{T_o} - R \ln\frac{P}{P_o} \right) \tag{27}$$

With the decomposition defined by Equation 24, the general exergy balance equation can be expressed as

$$\dot{E}^{CHE} + \left(\sum \dot{E}_{\iota}^{T} - \sum \dot{E}_{e}^{T}\right) + \left(\sum \dot{E}_{\iota}^{P} - \sum \dot{E}_{e}^{p}\right) + T_0\left(\sum \dot{S}_{\iota} - \sum \dot{S}_{e} + \dot{Q}_{CV}/T_o\right) = \dot{E}^{W} \tag{28}$$

The chemical exergy, $\dot{E}^{\mathrm{CHE}}$, for the various substances analyzed was taken from published standard chemical exergies .The total exergy of the inlet and exit streams is the sum of its physical and chemical components.

Total chemical exergy Equation

$$\dot{E}^{CHE} = \dot{E}^{\mathrm{PH}} + \dot{E}^{\mathrm{CH}} \tag{29}$$

The fuel for the combustion chamber at the AL Najaf plant is natural gas. For the purpose of this analysis, the physical and chemical properties of the fuel were assumed as methane gas. For the combustion products, the total physical and chemical exergies of the gas mixtures were calculated on a molar fraction basis. The equations for specific physical and chemical exergies for the gas mixtures are given below

Specific Physical Exergy-Gas Mixtures

$$E^{Ph} = \frac{\bar{h} - \bar{h}_o \ - T_o - \bar{S} - \bar{S}_o}{M} \tag{30}$$

$$\bar{h} = \sum_{K=1}^{N} x_k \ \bar{h}_k \tag{31}$$

$$\bar{S} = \sum_{k=1}^{N} x_k \, \bar{s}_k \tag{32}$$

$$M = \sum_{k=1}^{N} x_k M_k \tag{33}$$

The physical exergy of the combustion products can be found as

$$\dot{E}^{PH}=x_{co_2}\left[\left(h_{co_2}-h_{o_{co_2}}\right)-\ T_o\left(S_{co_2}-S_{c0_2}\right)\right]+x_{H2O}\left[\left(h_{H2O}-h_{o_{H2O}}\right)-\right.$$

$$\left.T_o\left(S_{H2O}-S_{o_{H2O}}\right)\right]+x_{O_2}\ \left[\left(h_{O2}-h_{oO_2}\right)-T_o\left(s_{O_2}-S_{o_{O_2}}\right)\right]+$$

$$x_{N_2}\left[\left(h_{\,N_2}-h_{o_{N_2}}\right)-T_o\left(S_{N_2}-S_{o_{N_2}}\right)\right] \qquad (34)$$

To find specific heat capacity of the combustion gases is obtained by equations of each component by equation (35) [62].

$$C_{P\ gas}=1.00397+\frac{2.429\,.T}{10^5}\ +\frac{1.63\ \ .T^2}{10^7}-\frac{6.966.T^3}{10^{11}} \qquad (35)$$

Where the unit of temperature is K.

Specific Chemical Exergy –Gas Mixtures as shown (36)

$$e^{CH}=\frac{\left(\sum_{k=1}^{N}x_k\ \ e_k^{CH}+\bar{R}\ \ T_0\ \sum_{k=1}^{N}x_k\ \ lnx_k\right)}{M} \qquad (36)$$

The subscript k in the above equations refers to individual component in the gas mixture, and M is the calculated overall molecular weight of the mixture and the chemical exergy for combustion is defined as

$$e^{CH}=\left(x_{co_2}.\bar{e}_{co_2}^{CH}+\ x_{\,H_2O}\,.\bar{e}_{H_2o}^{CH}+\ x_{\,O_2}.\bar{e}_{O_2}^{CH}+x_{N_2}.\bar{e}_{N_2}^{CH}\right)+\ \ \bar{R}T_o\left(x_{co_2}.lnx_{co_2}+\right.$$

$$\left.x_{H_2O}\,.lnx_{H_2O}\ +x_{O_2}.lnx_{O_2}+x_{N_2}.lnx_{N_2}\right) \qquad (37)$$

4.11 Exergy - Balance Equations for a Gas Turbine Plant

The exergy balance equation for each component in the AL Najaf Power station can be derived from the general exergy balance equation given in Equation 28. The exergy balance equations for each of these components are as follows based on figure 17:

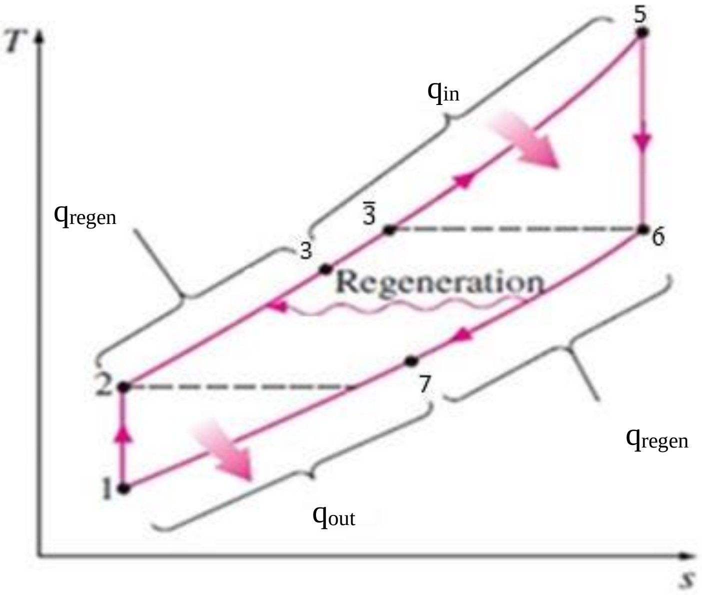


Figure 17 A Typical T- s Diagram of AL-Najaf Power Cycle

State 1-2 (compressor)

$$\left(\dot{E}_1{}^{T}-\dot{E}_2^{T}\right)+\left(\dot{E}_1^{P}-\dot{E}_2^{P}\right)+T_o\left(\dot{S}_1-\dot{S}_2\right)=\dot{W}_{AC} \tag{38}$$

State 2-3- 6-7(air –preheater)

$$\begin{aligned}&\left(\dot{E}_2^{T}-\dot{E}_3^{T}+\dot{E}_6^{T}-\dot{E}_7^{T}\right)+\left(\dot{E}_2^{P}-\dot{E}_3^{P}+\dot{E}_6^{P}-\dot{E}_7^{P}\right)\\&\qquad+T_o\left(\dot{S}_2-\dot{S}_3+\dot{S}_6-\dot{S}_7+\dot{Q}_{APH}/T_o\right)=0\end{aligned} \tag{39}$$

State 3 -4-5(combustion chamber)

$$\begin{aligned}&\dot{E}^{CHE}+\left(\dot{E}_3^{T}+\dot{E}_f^{T}-\dot{E}_5^{T}\right)+\left(\dot{E}_3^{P}+\dot{E}_f^{P}-\dot{E}_5^{P}\right)\\&\qquad+T_o\left(\dot{S}_3+\dot{S}_f-\dot{S}_5+\dot{Q}_{CC}/T_o\right)=0\end{aligned} \tag{40}$$

State 5-6 (Gas turbine)

$$\left(\dot{E}_5^{T}-\dot{E}_6^{T}\right)+\left(\dot{E}_5^{P}-\dot{E}_6^{P}\right)+T_o\left(\dot{S}_5-\dot{S}_6\right)=\dot{W}_{GT} \tag{41}$$

4.12 Exergy Destruction

Exergy is lost when the energy associated with a material or energy stream is rejected to the environment as a result of irreversibilities in the power plant.

The exergy destroyed during each process and for whole plant are written as follows in the table 3.

Plant Component	**Exergy Destroyed**
Air Compressor	$\dot{E}_{DAC} = T_o \left(\dot{S}_2 - \dot{S}_1\right)$
Air-Preheater	$\dot{E}_{DAPH} = T_o \left(\dot{S}_2 - \dot{S}_3 + \dot{S}_6 - \dot{S}_7 + \dot{Q}_{APH}/T_o\right)$
combustion chamber	$\dot{E}_{DCC} = T_o\left(\dot{S}_3 + \dot{S}_f - \dot{S}_5 + \dot{Q}_{CC}/T_o\right)$
Gas Turbine	$\dot{E}_{DGT} = T_o\left(\dot{S}_5 - \dot{S}_6\right)$
Total Exergy Destroyed in the Plant	$\dot{E}_{D\,plant} = \dot{E}_{DAC} + \dot{E}_{DAPH} + \dot{E}_{DCC} + \dot{E}_{DGT}$

Table 3: Expression for Exergy Destruction Rate for Plant

The exergy destruction efficiency can be compared to the rate of exergy flow of fuel in the plant. For each of the component exergy destruction efficiencies are written as follows in the table 4.

Plant Component	**Exergy Destruction Efficiency**
Air Compressor	$\varepsilon_{DA\,C} = \frac{\dot{E}_{DAC}}{\dot{E}^{CHE}}$
Air-Preheater	$\varepsilon_{APH} = \frac{\dot{E}_{DAPH}}{\dot{E}_{CHE}}$
combustion chamber	$\varepsilon_{DCC} = \frac{\dot{E}_{DCC}}{\dot{E}^{CHE}}$
Gas Turbine	$\varepsilon_{DGT} = \frac{\dot{E}_{DGT}}{\dot{E}^{CHE}}$
Total Exergy Destroyed in the Plant	$\varepsilon_{D\,plant} = \frac{\dot{E}_{D\,plant}}{\dot{E}^{CHE}}$

Table 4: Expression of Exergy Destruction for the Components and Plant

4.13 Exergy Efficiency

Exergy efficiency is defined as the ratio of useful exergy (output) to exergy supplied (input). The exergy efficiency for a system is written as

$$\eta = \frac{Useful\ Exergy}{Exergy\ Supplied} = 1 - \frac{Exergy\ destroyed}{Exergy\ Supplied} \tag{42}$$

Hence, the exegetic efficiency of the gas turbine power plant is evaluated for the various components and for the overall plant from the following equations

Air Compressor

$$\eta_{AC} = 1 - \frac{\dot{E}_{DAC}}{\dot{W}_{AC}} \tag{43}$$

Air-Preheater

$$\eta_{APH} = 1 - \frac{\dot{E}_{APH}}{\dot{E}^{CHE}} \tag{44}$$

Combustion Chamber

$$\eta_{cc} = 1 - \frac{\dot{E}_{Dcc}}{\dot{E}^{CHE}} \tag{45}$$

Gas Turbine

$$\eta_{GT} = 1 - \frac{E_{DGT}}{W_{GT}} \tag{46}$$

Overall Plant

$$\eta_{Plant} = 1 - \frac{\dot{E}_{D\ plant}}{\dot{E}^{CHE}} \tag{47}$$

4.14 Chemical Exergy Analysis

During a chemical reaction, the bonds between the molecules of reactants are broken. The atoms and electrons can then rearrange to form products. A physical requirement of chemical reactions is that mass is conserved. Therefore, the mass of the products must equal the mass of the reactants. The elements simply find themselves in different chemical compounds in the reactants, than they find themselves in the products. Despite the equality of mass between the reactants and products, the equality relation does not stand for the number of moles. The number of moles of the products may differ from the number of moles of reactants. Moreover, the chemical exergy is defined as the maximum useful work in a chemical process that brings the system into equilibrium with a heat reservoir. In some cases the ambient atmosphere is the reservoir of the system. Exergy, in this case, is the potential of that system to cause a change while achieving equilibrium with its environment. Exergy is the available energy for use in the system. Once the system and surroundings reach equilibrium, the exergy becomes zero. The chemical exergy of a fuel is defined by the Gibbs free energy function and the chemical exergy of the individual element present in the fuel. For a given fuel the function takes the form

$$e_f^{CHE} = \Delta_f G^o + \Sigma\, N_{x\ elements} \times e^{CH}{}_{element}\ \text{(kJ/mol)} \qquad (48)$$

The Gibbs free energy ($\Delta f G^o$) is a function of heating value and entropy of formation. It can be written as

$$\Delta_f G^o = \Delta_f H^o - T_o\, \Delta_f S^o\ \text{(kJ/mol)} \qquad (49)$$

Where $\Delta_f\, H^o$ represents formation enthalpy (kJ/mol).

The formation enthalpy is dependent on standard entropy of fuel (i.e. entropy at reference temperature and pressure) and standard entropy of elements present in chemical equation. It is expressed as

$$\Delta f\ S^o = S^o - \Sigma\ Nx_{\ element} \times\ S_f^o{}_{elements}\ \text{(J/mol .K)} \qquad (50)$$

Where N_x is the number of moles of the elements in the chemical equation in the formation of the substance. Usually standard (also called reference) thermo-physical properties are measured at a temperature of 298.15 K and at pressure of 1.0135 bar. The selected fuel in the current study is Methane (CH4) burned with 50 percent excess air. The chemical equation of the combustion process can be written in the form

$$CH_4 + 1.5\ a_{th}\ (O2+3.76N2) \longrightarrow XCO_2 + YH_2O + ZO_2 + WN_2 \qquad (51)$$

The elements in parentheses represent the dry air involved in the combustion reaction that contains 1 kmol of O_2. The unknowns X, Y, Z, W represent the mole numbers of the gases in the products. These unknowns are determined by applying the mass balance to each of the elements. Hence, since the total mass or mole number of each element in the reactants must equal that in products

$$CH4 + 1.5\ a_{th}\ (O_2+3.76N_2) \longrightarrow XCO_2 + YH_2O + 1.5a_{th}\ O_2 + (1.5*3.76)a_{th}N_2 \qquad (52)$$

C: $1 = X \longrightarrow X=1$

H: $4 = 2Y \longrightarrow Y = 2$

$$1.5\, a_{th} \times 2 = X \times 2 + Y \times 1 + 0.5_{ath} \times 2$$

$$a_{th} = 2$$

$$\longrightarrow Z = 1$$

$$\longrightarrow W = 11.28$$

$$CH_4 + 3(O_2 + 3.76N_2) \longrightarrow CO_2 + 2H_2O + O_2 + 11.28N_2 \quad (53)$$

The coefficient 3 in the balanced equation above represents the number of moles of oxygen, not the number of moles of air. The coefficient must be multiplied through the bracket contain the element representing dry air. Therefore, there would be 3 (1 × 3.76) moles of nitrogen and 3 moles of oxygen, for a total of 11.28 moles of air [63].

An approximate formulation for chemical exergy of gaseous hydrocarbon fuels is given as:

$$\frac{e_f^{CHE}}{\mathrm{LHV}} = 1.033 + 0.0169\frac{\mathrm{b}}{\mathrm{a}} - \frac{0.0698}{\mathrm{a}} \quad (54)$$

Where b = 77.647 and a = 11.933 for methane.

If the fuel is methane, a simpler relation may be given as [64].

$$\frac{e_f^{CHE}}{\mathrm{LHV}} \cong 1.06 \quad (55)$$

CHAPTER 5

RESULTS AND CONCLUSION

5.1 Results and Discussion

Table 5 shows chemical, thermal and mechanical exergy flow rates and entropy flow rates at various state points in the cycle. These flow rates were calculated based on the values of measured properties such as pressure, temperature, and mass flow rate at various points. Evaluations of various exergies at the inlet, and outlet of each system component are obtained by fitting appropriate polynomials (Gordon and Mcbride, 1971) to the thermo-physical data in the JANAF Tables (1971).

State	**Mass flow rate (kg/s)**	**temperature (K)**	**Pressure (bar)**	**$\dot{E}^{Ch}$ (MW)**	**$\dot{E}^{T}$ (MW)**	**$\dot{E}^{P}$ (MW)**	**$\dot{S}$ (MW/K)**
1	496.00	298.15	1.0135	0.00	0.00	0.00	0.00
2	496.00	602.00	8.6100	0.00	47.032	90.826	0.0452
3	496.00	795.90	8.2660	0.00	102.19	89.075	0.1906
4	10.500	298.15	30.000	558.1418	0.00	5.495	-0.01843
5	506.50	1319.0	8.0200	0.00	336.37	92.150	0.55708
6	506.50	860.50	1.0740	0.00	143.48	2.5829	0.06087
7	506.50	694.20	1.0340	0.00	83.91	0.8920	0.48929

Table 5 Property Values and Chemical, Thermal and Mechanical Exergy Flows and Entropy Production Rates at Different State Points in the Gas Turbine Plant

The net flow rates of the various exergies crossing the boundary of each component in the gas-turbine plant at rated conditions are shown in Table 6, together with the exergy destruction in each component. Positive values indicate the exergy flow rate of products while negative values represent the exergy flow rate of resources or fuel. Here, the product of a component corresponds to the added exergy whereas the resource to the consumed exergy [65]. The sum of the exergy flow rates of products, resources and destruction equals zero for each component and for the total plant; this zero sum indicates that exergy balances are exactly satisfied.

Component	**$\dot{E}^{W}$ (MW)**	**$\dot{E}^{Ch}$ (MW)**	**$\dot{E}^{T}$ (MW)**	**$\dot{E}^{M}$ (MW)**	**$\dot{E}_{D}$ (MW)**	**Ɛ(%)**	**η(%)**
Compressor	-151.32	0.00	47.o32	90.826	13.476	2.41	91.01
Air heater	0.00	0.00	-4.4083	-3.441	7.8979	1.41	97.20
Combustion chamber	0.00	-558.14	234.18	-2.420	326.37	55.77	56.77
Gas turbine	267.069	0.00	-192.89	-89.561	15.390	2.75	97.77
Total plant	115.74	-558.14	83.917	- 4.596	363.13	65.06	34.94

Table 6 Net Exergy Flow Rates, Exergy Destruction, Exergetic Destruction Efficiency and Exergetic Efficiency for the Gas Turbine Power Plant

Figure 18 shows the exergetic efficiency (η) of components of the gas-turbine plant. The exergetic efficiency of the total plant is also shown: it amounts to 34.94%. It is shown that the exergetic efficiency of the combustion chamber (56.77 MW) is much lower than that of other plant components, due to the high irreversibility in the combustion chamber

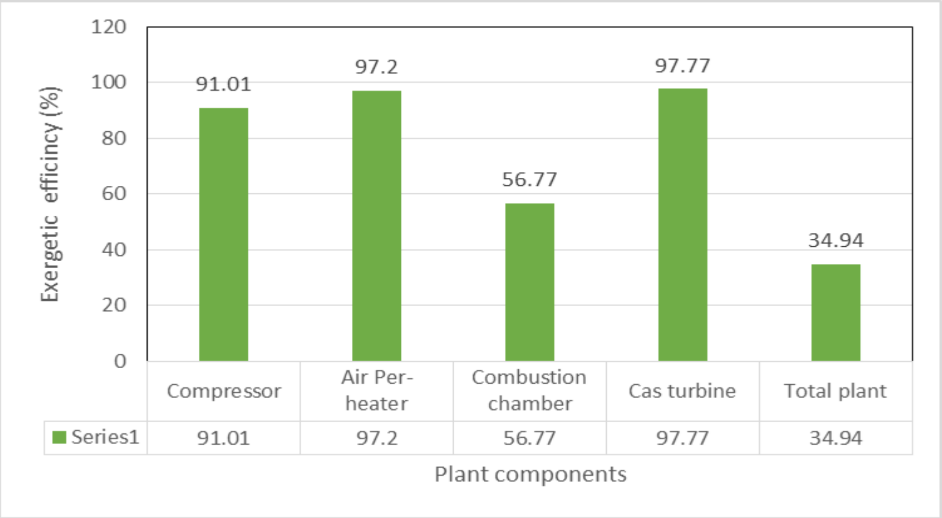


Figure 18 Exergetic Efficiency of Components and of Total Plant in the System

In comparison with other plant components, the combustion chamber destructs the largest amount of total inlet exergy into the plant, as shown in Figure 19. This figure shows also that 65.06% of the total inlet exergy is destroyed in the plant.

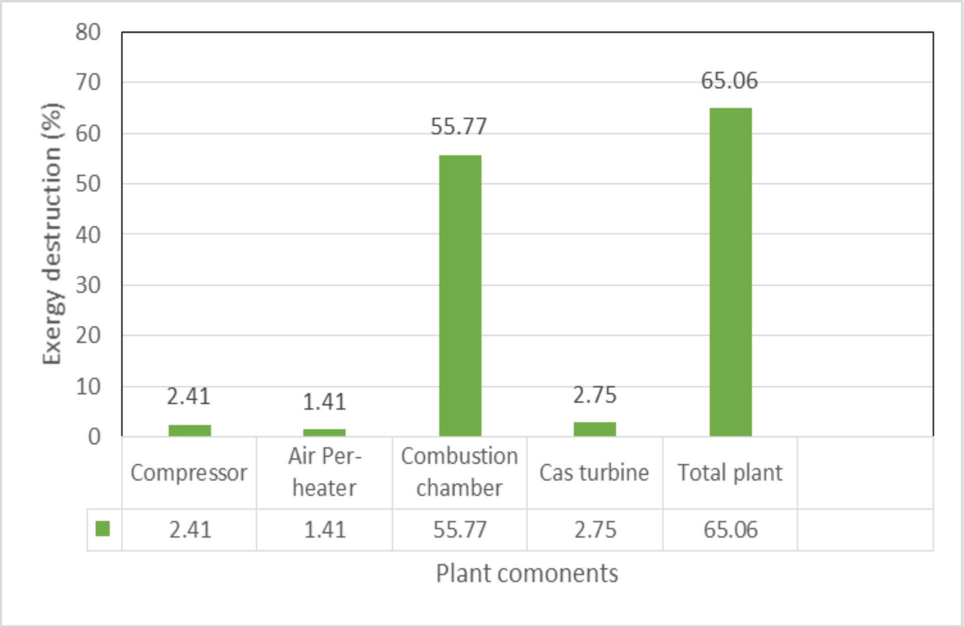


Figure 19 Exergy Destruction in Components and in Total Plant in the System

Exergy calculation was carried out for all the various operational values in Table 2 using an excel spread sheet and applying all described equations in Previous chapter. The summary of the calculations are presented graphically (Figures 20 -21).

Figure 20 compares the exergy efficiencies of the air compressor, combustion chamber, gas turbine and the overall plant of the GT at different ambient temperature values. The exergy efficiencies of the plant and the combustion chamber are found to decrease significantly with increase in the ambient temperature due to the high irreversibility($E_{Dcc} = T_o \times S_{gene\ cc}$) in the combustion chamber while slight increase in the air –perheater, the compressor and turbine exergy efficiency with increase in ambient temperature.

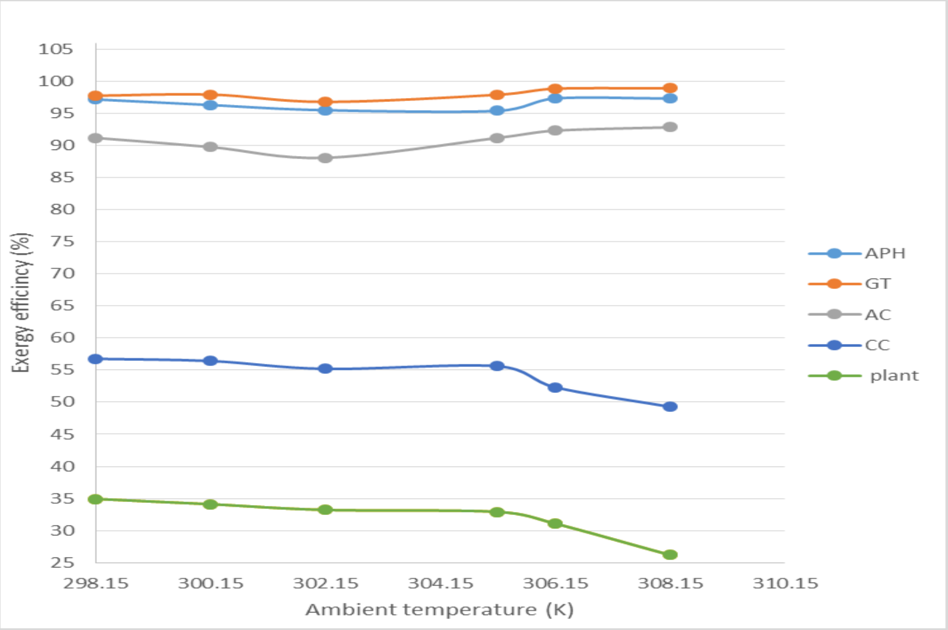


Figure 20 Change in Exergy Efficiency with Ambient temperature for Power Plant

Mass flow rate of air(m_a), mass flow of fuel (m_f), gas turbine work(W_{GT}) ,net power output gas turbine (W_{Net})and gas turbine efficiency are inversely proportional with ambient temperature while compressor work (W_c)is independent of ambient temperature.

When the gas turbine operates at varying ambient temperatures, the exergy loss at a lower ambient temperature is less than at a higher ambient temperature as shown in Figures 21.

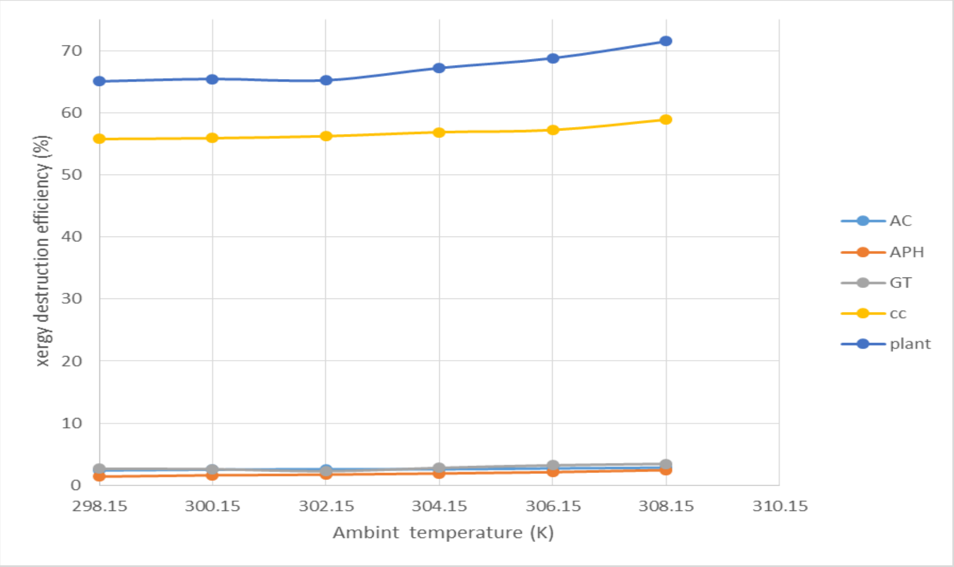


Figure 21 Change in Exergy Destruction Efficiency with Ambient Temperature for Power Plant

Figure 22 shows that the exergy efficiency of the plant increases steadily as the turbine inlet temperature increases. Which agrees with what, was obtained in [70]. The turbine inlet temperature (TIT) is an important parameter for gas turbines.

The exergy efficiency for GT, power output and pressure ratio are increased with increasing turbine inlet temperature (highest temperature in cycle T5)

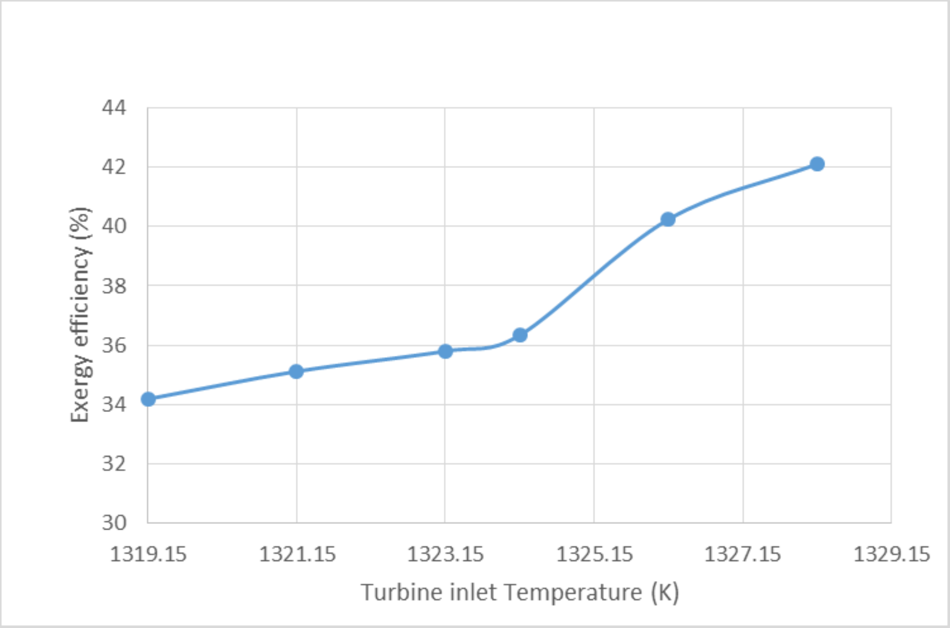


Figure 22 Change in Exergy Efficiency with Turbine Inlet Temperature for Power Plant

From Table 6 and Figure 23, the exergy flow rate of the net power output of the various gas turbine power units is found from the exergy balance to be 115.74 MW. The fuel exergy flow rate in the combustion chamber is found to be 558.14 MW for the Plant. The total exergy destruction in the plant calculated 363.134MW.The gas turbine is found to have the highest exergy efficiency of 97.77% in the plant. The combustion chamber exergy efficiency is 56.77%, which has the high – energy degradation and high irreversibility among the components considered. The exergy efficiency of the air compressor is 91.01% and largest is in the turbine section 97.77%. The exergy efficiency of the overall plant is 34.94%. The exergy efficiency for the plant and its various components are presented in Figure 18.

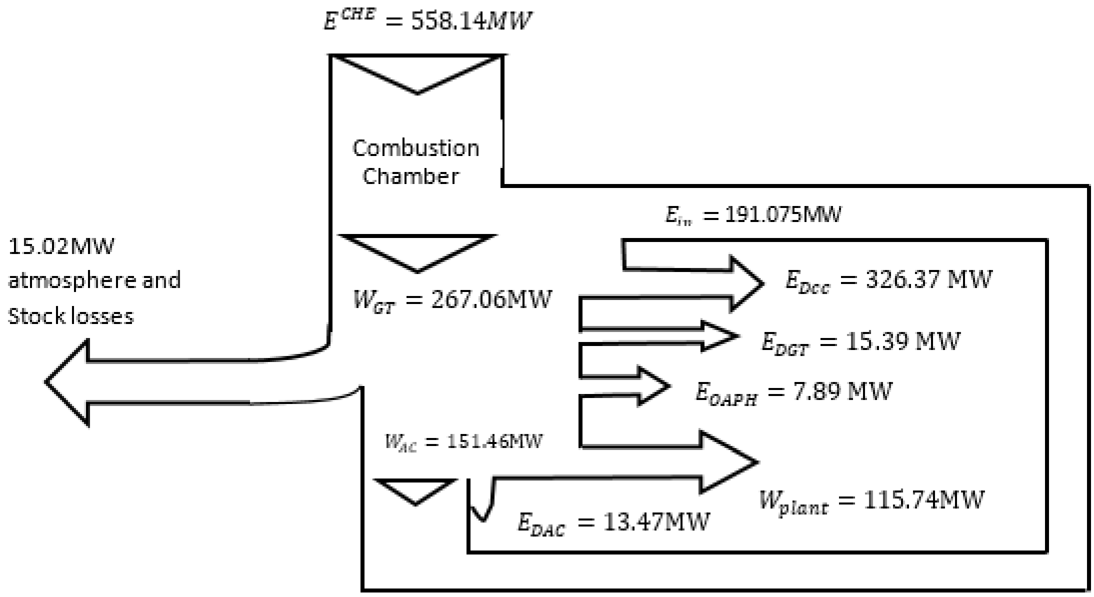


Figure 23 Grassmen Diagram for Plant

The exergy destruction efficiencies are presented in Figures 19 and 21, comparing the exergy destruction of the components of the gas power plant, the largest amount of the total exergy supplied in the plant is destroyed in the combustion chamber, the least exergy loss occurred in the gas turbine. It is observed that exergy destruction in the total plant is 65.06% of the total inlet exergy flow in the AL Najaf Gas Power Plant as shown in Figure 19. The values of components and total plant exergy efficiency and exergy destruction efficiency are in the same range as in [66, 67, 68] and disagree with [69] paper that stated the largest exergy destruction occurred in the turbine section.

5.2 Conclusion

Improving resource utilization is becoming increasingly important today, as the demand for high quality energy sources continues to grow. The practical application of the second law of thermodynamics is a useful tool in analyzing the quality of energy sources and how efficiently those sources are utilized in processes. While First Law concepts are valuable in analyzing thermodynamic processes, they do not provide the insight necessary to determine how efficiently resources are being utilized. Quantifying the quality of energy, or a substance’s availability to do useful work, is beneficial in the design of new systems as well as increasing the efficiency of existing systems.

This study examined the existing power plant at ALNajaf city from a Second Law perspective to determine the true system losses. Sources of exergy destruction were categorized and examined to determine feasible opportunities for efficiency improvements to enhance resource utilization. The major source of exergy destruction within the plant was determined to be the combustion chamber, primarily due to the irreversibilities associated with the combustion process. The combustion process within combustion chamber contributed to the total exergy destruction. However, the focus of the study was not on improving the combustion efficiency of the gas turbine power plant, but rather on discovering exergy destruction in the system. An exergy balance equation applied to a components or a whole power plant tells us how much of the usable work potential, or exergy, supplied as the input to the system under consideration has been consumed (irretrievably lost) by the process. The loss of exergy, or irreversibility, provides a generally applicable quantitative measure of process inefficiency. The effect of the turbine inlet temperature on the exergetic efficiency and on the exergy destruction in AL Najaf gas turbine power plant has been analysed. It was confirmed that the exergetic efficiency and exergy destruction in the combustion chamber are mainly affected by this parameter. Considerable exergy destruction occurs in the combustion chamber only, and therefore, both the exergetic efficiency and the exergy destruction in the power plant are affected mostly by the turbine inlet temperature. The results from the study also showed that considerable exergy destruction occurs in the combustion chamber; exergy efficiency, exergy destruction, power output depend on ambient temperature. Exergy efficiency increases with increase in the turbine inlet temperature. The excess heat in the combustion products could be utilized to serve additional thermal loads such as household water heating or space heating for nearby buildings. While these options were not explored, further improvements in Second Law efficiency would be achievable due to the increase in useful product exergy without increasing the amount of fuel consumed.

5.3 Future Work

In this thesis, advanced exergy techniques has been used to analyze AlNajaf gas turbine power plant, in order to assess exergy efficiency and exergy destruction of the system and its parts. The largest source of exergy destruction for all loads found in the combustion chamber. After accomplishing energy and exergy analysis that considered as basis for beginning thermoeconomic and sustainability analysis. Thermoeconomic and sustainability analysis are going to use for starting optimizing .It could be carried out for future works. Exergy and its links to environment is also an interesting topic. It is stated by the researchers that environmental problems such as air pollution, solid waste disposal, etc. may be reduced by using exergy techniques.

Exergy analyses provide useful information, which can directly impact process designs and improvements because exergy methods help in understanding and improving efficiency, environmental and economic performance as well as sustainability. Exergy's advantages stem from the fact that exergy losses represent true losses of potential to generate a desired product, exergy efficiencies always provide a measure of approach to ideality, and the links between exergy and both economics and environmental impact can help develop improvements

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APPENDIX A

CURRICULUM VITAE

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