CHAPTER 1

INTRODUCTION

1.1 Overview

The whole world is in the grip of energy crisis and the pollution manifesting itself in the spiralling cost of energy and uncomforted due to increase in pollution as well as the depletion of conventional energy resources and increasing curve of pollution elements. To meet these challenges one way is to check growing energy demand but that would show down the economic growth as first step and to develop non-polluting energy conversion system as second step. It is commonly accepted that the standard of living increases with increasing energy consumption per capita. Any consideration of energy requirement and supply has to take into account the increase conservation measures.

The amount of energy consumption increases continuously. The growing demand of energy which is the most important need for humanity has put forward the efficient energy utilization and environmental issues especially. Hence, the studies to more clean and efficient use of limited energy resources have been popular. In this regard, energy and exergy analysis are used for evaluating the performances of power production and consumption processes. The performance criteria outputs from energy balances deals with the “quantity” of energy, not the “quality” of energy. The thermodynamic quantity exergy, which can be used to assess and improve energy systems, can help better understand the benefits of utilizing green energy by providing more useful and meaningful information than energy provides.[1]

The effective use of natural resources in all aspects of society has become increasingly important, as technological advancement and population growth has increased the demand for high quality energy sources. The combined cycle system is widely used in the world from the energy crisis broke out in the 20st century 70's and the unit capacity which had put into operation has been more than 27400MW till 1996. [2]

1.2 Power Plant

A power plant is assembly of systems or subsystems to generate electricity, *i.e.*, power with economy and requirements. The power plant itself must be useful economically and environmental friendly to the society. While the stress is on energy efficient system regards conventional power systems *viz.*, to increase the system conversion efficiency the supreme goal is to develop, design, and manufacture the non-conventional power generating systems in coming decades preferably after 2050 AD which are conducive to society as well as having feasible energy conversion efficiency and non-friendly to pollution, keeping in view the pollution act. The industrial revolution led to the development of electric power, which quickly became very important to mankind. The need for electric power grew rapidly, and with it more efficient power-producing plants. Heat is the ability to change the temperature of an object or phase of a substance. For example, heat changes a solid into a liquid or a liquid into a vapour. Heat is part of the definition of energy.

At present due to energy crisis the first goal is to conserve energy for future while the second step is to develop alternative energy systems including direct energy conversion devices, with the devotion, dedication and determination remembering the phrase, “Delve and Delve Again till wade into”. A power plant may be defined as a machine or assembly of equipment that generates and delivers a flow of mechanical or electrical energy. The main equipment for the generation of electric power is generator. When coupling it to a prime mover runs the generator, the electricity is generated.[3] In thermal power stations, mechanical power is produced by a heat engine that transforms thermal energy, often from combustion of a fuel, into rotational energy.

1.3 Classification of Power Plants

There are two types of Power plants: Conventional and Non-Conventional.

- **Conventional Power Plants:** The sources of energy which have been in use for a long time, e.g., coal, petroleum, natural gas and water power.

- **Non-Conventional Power Plants:** The resources which are yet in the process of development over the past few years. It includes solar, wind, tidal, biogas, and biomass, geothermal.

Classification of various power plants is given in Fig.1.

Power Plants

- **Conventional**
  - Steam Engines Power Plants
  - Steam Turbine Power Plants
  - Diesel Power Plants
  - Gas Turbine Power Plants
  - Hydro-Electric Power Plants Plant
  - Nuclear Power Plants
- **Non-Conventional**
  - Thermoelectric Generator
  - Thermoionic Generator
  - Fuel cell power plant
  - Wave and Tidal Plant
  - Ocean Thermal
  - Biomass Energy Power System
  - Geothermal Energy

Fig.1 Classification of Power Plants

1.4 Current Scenario Of Power Plants In India

The present power position in India is alarming as there are major power shortages in almost all states of the country leading to crippling of industries and hundreds of thousands of people losing jobs and a heavy loss of production. The overall power scene in the country shows heavy shortages almost in all states. The situation is going to be aggravated in coming years as the demand is increasing and the power industry is not keeping pace with the increasing demand. Many of the states in India depend to a large extent on hydro generation. The increase in demand has far outstripped the installation of new plants. Also there is no central grid to distribute excess energy from one region to another. The experience in the operation of thermal plants is inadequate. All these have led to heavy shortages and severe hardship to people. Very careful analysis of the problem and proper planning and execution is necessary to solve the power crisis in our country. Suitable hydrothermal mix, proper phasing of construction of new plants, training personnel in maintenance of thermal plants.

1.5 Future Power Generation in India

As per the present planning of the Government, the problem of increased power demand will be solved only by proper mixed development of hydro-electric, thermal and nuclear at least during one more decade. The severity of the power problem can be partly solved by the conservation of power. The efficiency of thermal power plant is 35%. In India, it is hardly 25%. If auxiliary consumption and line loss are taken into account, the efficiency still goes to hardly 16%. The problem can be partly solved by proper maintenance and good quality of fuel supply.

The efficiency of the power plant operation is also defined as kWh generated per kW installed. The maximum kWh per annum per kW is 8760. The average Figure in India is hardly 4000, which shows that the utilization is only 45%. If this utilization is increased, need to incorporate new capacity for power generation will be reduced. Increasing load factors can reduce the capacity of the power industry. The proper planning to develop hydro-electric, thermal and nuclear resources in India in addition to measures taken to reduce outages and with proper load management will definitely go a long way in meeting the increasing power demand of the country.

The world energy needs really heavily on fossil fuels for electricity generation. The majority of the world's power generation is met by fossil fuels, particularly coal and natural gas. Despite the growth of renewable energy installations like wind and solar power, the heavy dependence on fossil fuels is expected to continue for decades. Despite the depletion of fossil fuel reserves and environmental concerns such as climate change, the growth in oil demand is expected to be 47.5% between 2003 and 2030, 91.6% for natural gas and 94.7% for coal. Even though cleaner renewable sources of energy are being rapidly developed, their relative cost and current state of technology have not advanced to a stage where they can significantly reduce our dependence on fossil fuels. Therefore, given the continued reliance on fossil fuels for some time, it is important that fossil fuel plants reduce their environmental impact by operating more efficiently. [4]

1.6 Basics of Exergy Analysis:

1.6.1 Thermodynamic Analysis

Thermodynamics can be defined as the science of energy. Thermodynamics is the study of energy interactions between systems and the effect of these interactions on the system properties. Energy transfer between systems takes place in the form of heat and work. For thermodynamic analysis the first and second laws are used simultaneously.

1.6.2 First Law of Thermodynamics

The first law of thermodynamics, also known as the conservation of energy principle, provides a sound basis for studying the relationships among the various forms of energy and energy interactions. The first law of thermodynamics states that energy can be neither created nor destroyed during a process; it can only change forms. Therefore, every bit of energy should be accounted for during a process.

$$\begin{pmatrix} Total\ energy \\ entering\ the\ system \end{pmatrix} - \begin{pmatrix} Total\ energy \\ leaving\ the\ system \end{pmatrix} = \begin{pmatrix} Change\ in\ the\ total \\ energy\ of\ the\ system \end{pmatrix}$$

Or

$$E_{in} - E_{out} = \Delta E_{system} \qquad (1.1)$$

Energy balance equations for closed and steady flow system are given as below:

- **Energy balance for closed system**

$$Q_{net,in} - W_{net,out} = \Delta E_{system} \ or \ Q - W = \Delta E \tag{1.2}$$

where, $Q = Q_{net,in} = Q_{in} - Q_{out}$ is the heat input, $W = W_{net,out} = W_{out} - W_{in}$ is the net work output.

- *Stationary System:* $Q - W = \Delta U$

As $\Delta KE = 0, \Delta PE = 0 \ and \ \Delta E = \Delta U$

- *Per unit mass:* $q - w = \Delta e$
- *Differential form:* $\delta q - \delta w = de$

System undergoing cycle: $Q - W = 0 \ or \ Q = W$ (initial and final points are same)

- **Energy balance for Steady-Flow system**

  Steady-flow process is the process during which fluid flows through a control volume steadily.

  Mass balance: $\sum \dot{m}_{in} = \sum \dot{m}_{out}$

1.6.3 Second Law of Thermodynamics

The second law of thermodynamics, which asserts that processes occur in a certain direction and that energy has quality as well as quantity. A process cannot take place unless it satisfies both the first and second laws of thermodynamics. The second law of thermodynamics is a limit law. It can be used in determining the theoretical limits for the performance of commonly used engineering systems, such as heat engines and refrigerators, as well as predicting the degree of completion of chemical reactions.

1.7 Exergy Analysis

Exergy is defined as the maximum theoretical useful work that can be obtained as a system interacts with an equilibrium state. The exergy is not generally conserved like energy but is destroyed in the system. Exergy analysis is a powerful tool in the design, optimization, and performance evaluation of energy systems. An Exergy balance applied to a process or a whole plant tell us how much of the usable work potential, or Exergy supplied as the inlet to the system under consideration has been consumed

(irretrievably lost) by the process. The Exergy destruction or irreversibility provides a generally applicable quantitative measure of process inefficiency. Analysing a multi-component plant indicates the total plant irreversibility distribution among the plant components, pinpointing those contributing most to overall plant inefficiency [5].
Exergy analysis is useful for improving the efficiency of energy-resource use, since it quantifies the locations, types and magnitudes of losses.

1.7.1. Exergy Destruction(ED)

Irreversibilities such as friction, mixing, chemical reactions, heat transfer through a finite temperature difference, unrestrained expansion, non-quasi-equilibrium compression or expansion always generate entropy, and anything that generates entropy always destroys exergy. Exergy destroyed is a positive quantity for any actual process and becomes zero for a reversible process. Exergy destroyed represents the lost work potential and is also called the irreversibility or lost work.

1.7.2. Total Exergy Destruction

It is the sum of exergy destruction in different components of the system. Second law of thermodynamics provide the means of assigning a quality index to energy. The concept of exergy provides a useful measure of energy quality. Second law efficiency or exergetic efficiency is defined as the ratio of minimum exergy required to do a given task to the actual exergy consumed in performing the same task. [6]

1.7.3 Exergetic Efficiency

It is also called second law of Efficiency. The exergetic efficiency, or Second Law efficiency, is a useful tool in evaluating the true thermodynamic performance of a particular system because it indicates how much of the available energy is translated to useful work.

$$\eta_{exergetic} = \frac{\text{Total rate of exergy output}}{\text{total rate of exergy input}}$$

CHAPTER 2
LITERATURE REVIEW

Analysis of the power plant is a broad concept involving the efficient use of energy resources. In earlier days, the energy efficiency of the plant was analyzed based on the first law of thermodynamics. But in recent times, the second law of thermodynamics has been widely used to determine exergy losses because it is related directly to quality of energy produced within the system.

Regulagadda et al. [3] has done thermodynamic analysis of a subcritical boiler–turbine generator for a 32 MW coal-fired power plant. Both energy and exergy formulations are developed for the system. A parametric study was conducted for the plant under various operating conditions, including different operating pressures, temperatures and flow rates, in order to determine the parameters that maximize plant Performance. From the analysis of a power plant, it was determined that the efficiency is 30.16 % for the gross generator output. It was found that the plant exergy efficiency for the system was 25.38 %. The maximum exergy destruction was found to occur in the boiler. It was also reported that the improving the efficiency of a boiler is directed to the improvement of efficiency of the plant.

Aljundi [7] has done the modelling of a steam power plant in Jordan to determine the energy and exergy losses. In his study, energy and exergy analysis as well as the effect of varying the reference environment temperature on the exergy analysis of an actual power plant has been investigated. It was reported that the maximum energy loss was found in the condenser was 66% of the input energy was lost to the environment in the considered cycle. It was also reported that the energy lost in the boiler system was about 6% and less than 2% for all other components.

Karthikeyan et al. [8] provide energy balance for a one pressure level heat recovery steam generator. He discussed the pinch and approach points on steam generation and also on temperature profiles across heat recovery steam generator. In this system he also concludes the effect of operating condition on steam production and also On exit gas temperature from the heat recovery steam generator are also discussed. He also discussed that low pinch point results in improved heat recovery steam generator performance due to reduced irreversibility. On the other hand he also discussed that supplementary firing enhance the steam production.

Habib et al. [9] presented an analysis of a cogeneration system. The analysis gives the quantity of irreversibility of the different component of the plant and the on the other hand he has also observed the effect of heat to power ratio and the process pressure on the thermal efficiency The utilization factor is also discussed. He shows his result in his research that the irreversibility of the cogeneration plant is approximated 38% low as compared to the other plant or conventional plant. This value reduces due to the increase in thermal efficiency and utilization factor by 24% to 25% respectively and result shows that exergy destruction in the boiler is high.

Huang et al. [10] have conducted the performance evaluation study .The versatility of the analyzed system has been observed by using an advanced gas turbine as the prime mover. The high power to heat ratio and high quality of energy has been reported in the research conducted.

Zhao et al. [11] presented a performance analysis model of gas-steam combined cycle with coke oven gas according to the layout of the actual industry. The exergy analysis and calculation are carried for the specific working conditions so as to provide guidance for the practical operation in the industry. The thermal efficiency is higher than the exergy efficiency. The thermal efficiency of the total system is 71.42%, and the exergy efficiency is 62.46%. The exergy efficiency can reflect the situation of energy utilization.

Hasti et al. [12] has done the exergy analysis for ultra super-critical power plant. The analysis was carried out by means of process simulation using a computer model developed in Microsoft excels. The model was based on the concepts of coal combustion, energy balances, enthalpy balances, entropy changes and heat transfer of the steam power cycle. The maximum Energy loss was found in the condenser followed by the furnace system. Upon applying the second law of thermodynamics into the analysis, the exergy losses can be determined. It was reported that the exergy loss in the furnace was 86% and its relevant exergy destruction was 615 MW. The exergy destruction in the condenser was relatively less than the furnace which was 15 MW and its exergetic efficiency reported was 70%. The exergy destruction is observed higher in the turbine having 45 MW of loss with average of 82% exergetic efficiency. It was shown that the exergy loss is higher in the furnace followed by the turbine. An effort to reduce the exergy loss in the furnace was made and a part of available heat is retrieved after the combustion process and used in the air pre-heater to preheat the fuel. It was also reported that exergy destruction rate loss was found to reduce in the furnace to a percent of 71%.

Sahin et al. [13] has done the energy and exergy analyses of Atlas İskenderun Power Plant. The plant was designed to operate at supercritical steam conditions with 600 MW output. The energy and exergy flow rates, Irreversibilities and efficiencies of each unit were determined by using IAPWS-IF97 formulation and thermodynamic equations.

Energy and exergy efficiency of the supercritical power plant in rated operation conditions were found 44,17% and 40,83% respectively. It was found that, most of the energy loss occurs in the condenser with 659,16 MW and most of the exergy loss occurs in the boiler with 761,097 MW. Therefore, efforts at improving the performance of the power plant should be directed at improving the boiler performance, since this will lead to the largest improvement to the plant’s efficiency.

It was also reported that the exergy efficiency of the power plant decreased when the reference ambient temperature increased. It was found that 1°C increase in the reference ambient temperature caused 0.14% decrease in energy efficiency and 0.12% of exergy efficiency the of power plant.

Ameri et al. [14] evaluated the irreversibility of each part of Neka Combined Cycle Power Plant (CCPP) using the exergy analysis. The results shown that the combustion chamber, gas turbine, duct burner and heat recovery steam generator (HRSG) are the main sources of irreversibility representing more than 83% of the overall exergy losses.

The first law efficiency and the exergy efficiency of CCPP were calculated. Thermal and exergy efficiencies of Neka CCPP were 47 and 45.5% without duct burner, respectively. The results show that when the duct burner is added to HRSG, these

efficiencies were reduced to 46 and 44%. It was also reported that that the CCPP output power increases by 7.38% when the duct burner was used.
The results showed that the exergy efficiency of the combustion chamber is much lower than the efficiency of other gas turbine components due to its high irreversibility. The second major exergy loss is in HRSG. Optimization of HRSG has an important role in reducing the exergy loss of total combined cycle.

Xiaodan et al. [15] has studied hydrogen-fuel combined cycle, including the balance of the material and energetic flows, the thermal efficiency and the exergy efficiency were calculated to evaluate the overall performance of the cycle. A proper parametric analysis was done to investigate the influence of the main working parameters on the cycle efficiency. The main factors such as temperature and pressure have strong effects on the large amount of exergy losses that are caused due to the process of combustion.

It was reported that the thermal efficiency and the exergy efficiency can reach to 61.37% and 62.9%respectively at 1500K temperature, 15Mpa pressure. It was also shown that the exergy losses in two combustion chambers and heat recovery exchanger (HRE) are the major. Improving the combustion temperature as much as possible, as well as decreasing the temperature differences of HRE, will reduce the exergy losses effectively. The maximum temperature and pressure influence the cycle efficiency. Through the optimization of systematic parameters and introducing the regenerative system, the cycle will achieve higher performance.

Enadi et al. [16] investigated three different conFigurations of CCPP. Three different HRSG cycle conFigurations are chosen and parametric analysis is carried out based on exergy analysis to see the effects of main cycle parameters on cycle efficiency. These are single pressure HRSG cycle, dual pressure HRSG cycle and triple pressure HRSG cycle. In single pressure cycle, HRSG generates steam at one pressure level. In dual pressure cycle, HRSG generates steam at two different pressure levels (high and low pressure). In triple pressure cycle, HRSG generates steam at three different levels (high, intermediate and low). Second law analysis was performed to get exergy destruction throughout the steam plant. Second law efficiency values were also obtained for single, dual and triple pressure steam cycle conFigurations. It was reported that maximum lost work due to irreversibility was in HRSG for a steam cycle in a single pressure HRSG cycle. It was also shown that the dual pressure and triple pressure cycles makes better use the exhaust gas in the HRSG than that of single pressure cycle.

It was shown that the exergy destruction of the combustion chamber is greater than other components. It was also concluded that as the chemical reaction takes place in CC, the exergy efficiency will reduce. Moreover, it was also shown that after CC, GT Turbine and HRSG are two other sources of exergy destructors. The total cycle efficiency is about 49%.

Jonshagen et.al [17] addresses the effects of mixing low-calorific fuel in to a natural gas fuelled large size combined cycle plant. Three different bio fuels are tested namely; air blown gasification gas, indirect gasification gas and digestion gas. He performed a Simulations model from 0-100% bio fuel – natural gas mixtures. He reported that in the gas turbine, the distortion in mass flow between the compressor and turbine is a limiting factor. The compressor will be strained as the cycle pressure rises to allow for the larger flow through the turbine. Below a LHV of approximately 20 MJ/kg, the fuel mass flow increases dramatically which indicates that it is not realistic to operate a standard gas turbine below this level.

Sreeramulu et al. [18] investigated a Combined cycle power plants have higher efficiency than those of recuperated gas turbine and atmospheric fuel cell, because exergy losses of combustion are made much smaller. An increase in compression ratio results in lower rate of exergy destruction of the plant and he also determine that an increase in turbine inlet temperature and ambient temperature results in higher rate of exergy destruction of the plant. A certain pressure ratio gives the highest generation efficiency, but its variation near the optimum point does not lead to a remarkable difference. He found that the exergy destruction in SOFC is maximum, though it is an efficient device. Exergy analysis of each component provides better understanding of losses at various states of the system operation of the plant at high efficiency.

2.1 Research Gap

We find that in power plant a large amount of heat energy goes as a waste in boiler with the exhaust of the gas turbine. Currently available systems include; steam turbines, gas turbines, combined cycle and reciprocating engines. In separate production of electricity, some energy must be discarded as waste heat, but in cogeneration this thermal energy is put to use.

2.2 Objective of Present Work

The objective of this type of approach is to use all of the heat energy in a power system at the different temperature levels at which it becomes available to produce work, or steam, or heating of air or water ,therefore rejecting a minimum of energy waste . Calculating the exergy losses in various component in power plant and find that where is the maximum exergy loss occurred. The influence of reference ambient temperature on the efficiencies and Irreversibilities of power plant have been investigated. Power plants and especially the boiler emit large quantities of waste heat and solid particulates in the boiler flue gas emissions. Losses due to heat carried away by the flue gas (stack losses) and the particulate content in the flue gas also causes adverse impact on the environment. To achieve better environmental sustainability, it is necessary not only to use sustainable or renewable sources of energy, but also to utilize non-renewable sources like coal more effectively, while minimizing the damage to the environment. This will enable society to maximize its use of limited resources and make existing resources last longer. Exergy clearly identifies efficiency improvements and reductions in thermodynamic losses attributable to green technologies. Exergy can also identify better than energy the environmental benefits and economics of energy technologies. Thus, exergy has an important role to play in increasing utilization of green energy and technologies.

CHAPTER 3
METHODOLOGY

3.1 Combined Power Plant Cycle System:

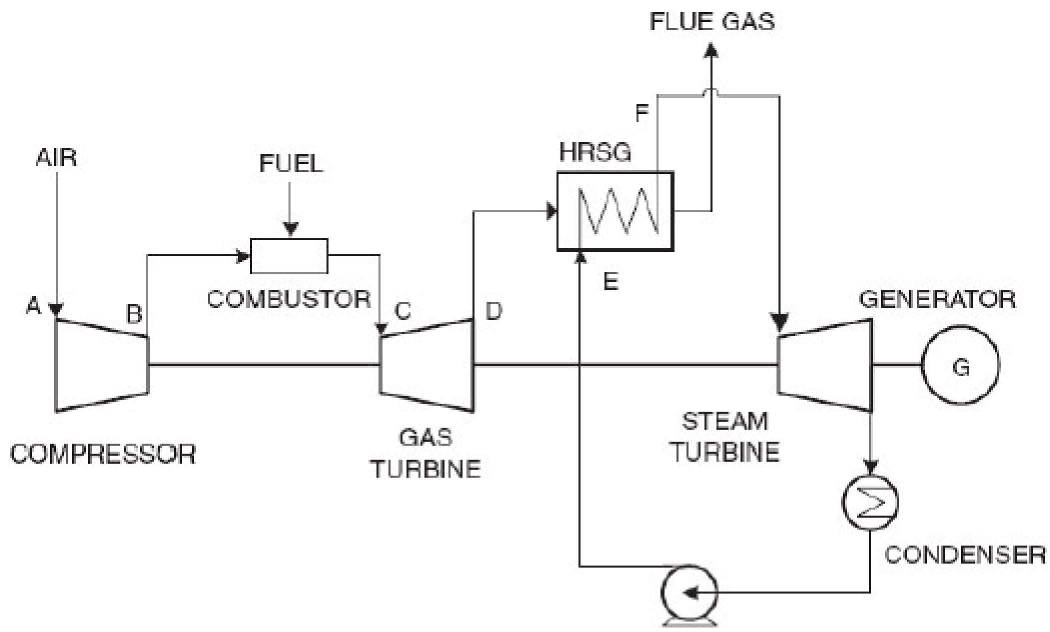

Figure: 3.1 combined cycle process [19]

Figure 3.1 shows a combination of an open cycle gas turbine and steam turbine .The exhaust of gas turbine which has high oxygen content.

The steam power plant gets its input heat from the high temperature exhaust gases from gas turbine power plant. This heat is utilized to generate steam in a steam generator. Thus the steam generated is used to drive steam turbine.

Hence, Combining the two or more thermodynamic cycles results in improved overall efficiency, reducing fuel costs In stationary power plants, a widely used combination is a gas turbine (operating by the Brayton cycle) burning natural gas or synthesis gas from coal, whose hot exhaust powers a steam power plant (operating by the Rankine cycle). This is called a Combined Cycle Gas Turbine (CCGT) plant. [19]

3.2 T-S diagram for Combined Power Plant Cycle System:

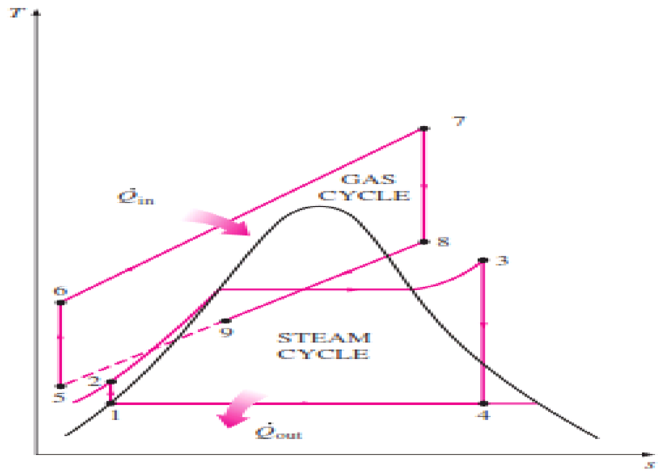

Figure: 3.2 T-S diagram of combined cycle [19]

Combined cycle:

Combined cycle consists of two cycles, one is Brayton Cycle(Gas Power Cycle) and another is Rankine Cycle (Steam Power Cycle).Heat from the exhaust of the gas power cycle is utilized to generate steam in steam power cycle. Further this steam is used to generate power in a steam power cycle.

1. **Brayton Cycle:** The cycle 5-6-7-8-5 which is the gas turbine power plant cycle is the topping cycle. The simple Brayton Cycle consist of four processes which are explained as below:

- **Process 5-6**: In process 5-6, a compressor is used to compress the air to high pressure and high temperature.
- **Process 6-7**: In process 6-7, a boiler is used to supply heat to highly compressed air at constant pressure.
- **Process 7-8**: In process 7-8, air is expanded through a gas turbine to get a net work output.
- **Process 8-5**: In process 8-5 heat rejection process at constant pressure occurs in a condenser as exhaust.

The exhaust gas from the gas turbine is at very high temperature is utilized to generate steam in a steam generator.

2. **Rankine cycle:** The cycle 1-2-3-4-1 which is the Rankine steam cycle takes place at a low temperature and is known as the bottoming cycle. The cycle consist of four processes which are explained as below:

- **Process 1-2**: Isentropic compression (Pump); during the isentropic compression process, external work is done on the working fluid by the pumping. Pumping takes place from low to high pressure.
- **Process 2-3**: Isobaric heat supply (Steam Generator or Boiler)*;* heat from the high temperature source is added to the working fluid to convert it into superheated steam.

  Pressurised liquid enters a boiler where it is heated at constant pressure to dry saturated vapour.
- **Process 3-4**: Isentropic expansion (Steam turbine); an isentropic process, the entropy of working fluid remains constant. The dry saturated vapour expands through a turbine, generating power. The temperature decreases and pressure drops, and condensation can take place may occur.
- **Process 4-1**: Isobaric heat rejection (Condenser); an isobaric process, in which the pressure of working fluid remains constant. The wet vapour then enters a condenser where it is condensed at a constant temperature to become a saturated liquid.

3.3 Exergy analysis:

Energy Equation solver is powerful computational mathematical tool which help in optimization of system by using various equation of system. Following equations of Combined Power plant cycle are considered to make a EES program and calculate the exergy losses in various components of a Combined Power Cycle. [20, 21]

Exergy destruction due to irreversibility in various components in the plant is given: [22,23]

1. Compressor

Lost work or Exergy dissipation $I_{Compressor} = W_a T_a (S_2\text{-}S_1)$ (3.3.1)

Where $(S_2\text{-}S_1) = C_p \ln \frac{T_2}{T_1} \text{-} R_a \ln \frac{P_2}{P_1}$ (in Air)

2. Combustor

Rate of Exergy dissipation or lost work

$$I_{Combuster} = \left[\left[W_g\, C_p \ln \frac{T_3}{T_0} - W_g\, R_g \ln \frac{P_3}{P_0}\right] - \left[W_g\, C_p \ln \frac{T_2}{T_0} - W_a\, R_a \ln \frac{P_2}{P_0}\right]\right] \quad (3.3.2)$$

3 **Gas turbine**

Rate of Exergy dissipation or lost work

$$I_{GT} = W_g\, T_0\, (S_4\text{-}S_3) \quad (3.3.3)$$

Where $(S_4\text{-}S_3) = C_p \ln \frac{T_4}{T_3} \text{-} R_g \ln \frac{P_4}{P_3}$ (in Gas)

4. **Heat recovery steam generator [HRSG]**

Rate of Exergy dissipation or lost work

$$I_{HRSG} = T_0 [\, W_s (S_a - S_e) + W_g (S_6 - S_4)] \quad (3.3.4.)$$

5. **Steam turbine**

Rate of Exergy dissipation or lost work

$$I_{ST} = W_s\, T_0\, (S_b\text{-}S_a)$$

Rate of Exergy dissipation or lost work

$$I_{ST} = W_s\, T_0\, (S_b\text{-}S_a) \quad (3.3.5)$$

6. **Exhaust loss**

Rate of Exergy dissipation or exergy loss due to flue gases

$$I_{exh} = W_g\, C_p [\, (T_6\text{-}T_0)\text{-}\ T_0 \ln \frac{T_6}{T_0}\ ] \quad (3.3.6)$$

$$\eta_{exergetic} = \frac{\text{Total rate of exergy output}}{\text{total rate of exergy input}}$$

Steady-flow energy equation:

$$\dot{Q}_i + \dot{W}_i + \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i\right) = \dot{Q}_e + \dot{W}_e + \sum \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e\right) \tag{3.3.7}$$

$$\boldsymbol{\eta_I} = \frac{\textbf{Desired output energy}}{\textbf{Input energy supplied}}$$

The energy or first law efficiency $\boldsymbol{\eta_I}$ of a system and/or system component is defined as the ratio of energy output to the energy input to system/component i.e.

Exergy balance for a control region undergoing a steady-state process is expressed as [22,24]

$$\dot{\mathrm{X}}_i + \dot{\mathrm{X}}_{\mathrm{j}}^{\mathrm{Q}} =$$

$$\dot{\mathrm{X}}_e + \dot{\mathrm{W}}_{\mathrm{j}} + \mathrm{E\dot{D}}_{\mathrm{j}} \tag{3.3.8}$$

$$\dot{\mathrm{X}}_i = \sum_{\mathrm{IN}} \dot{\mathrm{m}}\, x \tag{3.3.9}$$

$$\dot{\mathrm{X}}_e = \sum_{\mathrm{OUT}} \dot{\mathrm{m}}\, x \tag{3.4}$$

$$\dot{\mathrm{X}}_{\mathrm{j}}^{\mathrm{Q}} = \sum \left[\dot{\mathrm{Q}}_{\mathrm{j}} \frac{\mathrm{T} - \mathrm{T_o}}{\mathrm{T}}\right] \tag{3.3.10}$$

$$x = (\mathrm{h} - \mathrm{T_o s}) - (\mathrm{h_o} - \mathrm{T_o s_o}) \tag{3.11}$$

Where the first term on left hand and right hand side represent physical exergy (neglecting kinetic, potential and chemical exergy component) of stream of matter entering and leaving the control region respectively. The second term on left hand side and right hand side is thermal exergy flow, which gives exergy transfer rate corresponding to the heat transfer rate $\dot{\mathrm{Q}}$ when the temperature at the control surface where heat transfer is occurring is T and exergy associated with work transfer to and from the control region. $\mathrm{E\dot{D}}$ Represents rate of exergy destruction.

CHAPTER-4

RESULTS AND DISCUSSION

A mathematical computational model is developed for performing the energy and exergy analysis of the system using EES software.

The input data for the calculation of results in given in Table.4.1:

Table.4.1 Input data to calculate exergy loss in various components

Inlet temperature in compressor	298 to 316 K
Pressure ratio	4 to 13
Inlet Pressure steam turbine	40 bar
Condenser pressure	0.4 to 9.4
Feed water temperature	170
Pressure drop in HRSG	0.04 bar
Steam flow rate	28.35 kg/s
Specific heat ratio of air	1.4
Specific heat ratio of gas	1.33
Pressure ratio of the compressor	8
Pressure drop in the combustion chamber	0.03

In the table 4.1 the inlet condition of air (specific heat ratio-1.4) to the gas turbine power plant compressor is 1 bar and 298K. Air is compressed to a compression ratio 8 in the compressor, and then it is expanded in the gas turbine. Inlet pressure to the steam turbine is kept approx. 40 bar. Then air is expanded through the steam turbine to a condenser pressure about 0.45-9.4 bar. There is a Condition of steam at inlet to the steam turbine pressure drop of gas in HRSG is .04 bar.

RESULT

- Exergy destruction for various components of combined cycle is shown in Table 4.2. and Fig.4.1

Table 4.2 Exergy Destruction in various Components

Component	Exergy Destruction(kW)
Compressor	6515
Combustor	88500
Gas turbine	5540
HRSG	7330
Steam turbine	6320
Exhaust gases	16620

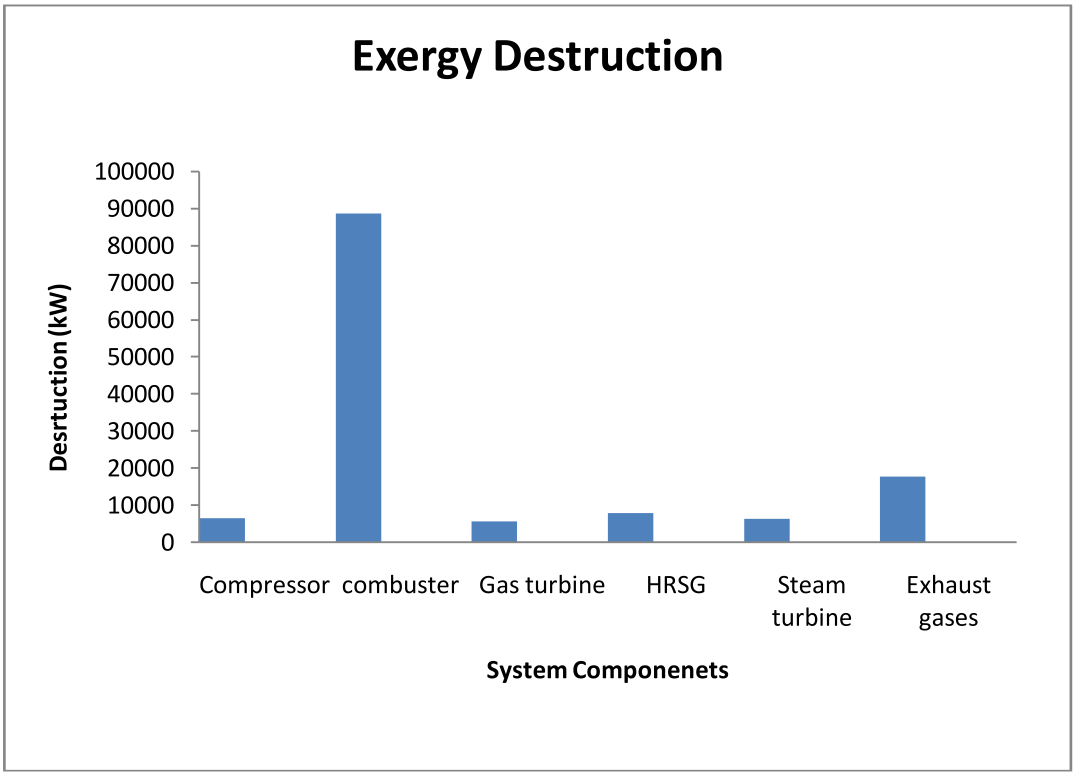

Fig.4.1 Exergy destruction in various component

It is quite clear from Fig. 4.1 that the maximum exergy destruction occurs in the combustion chamber (88550 kW), followed by destruction due to exhaust gases (16620 kW), HRSG (7330 kW), compressor (6515 kW), steam turbine (6320 kW), and least destruction in gas turbine (5540 kW).

Variation of Exergy loss with respect to ambient temperature in various parts of the Cycle power plant is shown in Table.4.3. In the combustion chamber, the minimum value of exergy destruction is 86440 kW at the temperature of 316 K and the maximum value (88580 kW) at the temperature 302 K. It is observed that there decrease in exergy loss with increase in ambient temperature.

It is also observed that the overall exergy loss in the plant with increase in ambient temperature

Table.4.3 Losses in various components w.r.t ambient temperature

T1[k]	I_{comb}	I_{comp}	I_{exh}	I_{hrsg}	I_{st}	I_{gt}
298	88580	7317	17691	7847	6267	5681
300	88359	7389	17342	7899	6267	5681
302	88133	7461	16996	7952	6309	5719
304	87904	7535	16655	8005	6351	5757
306	87670	7609	16319	8057	6393	5796
308	87432	7684	15986	8110	6435	5834
310	87190	7759	15657	8163	6477	5872
312	86944	7835	15333	8215	6519	5910
314	86694	7912	15012	8268	6561	5948
316	86440	7989	14696	8321	6603	5986

It is clear from the table 4.4 that exergetic efficiency is minimum (30.92%) at temperature 316K and maximum value (32.7 %) is obtained at a temperature of 298 K. It is clear from the table that gas plant efficiency is minimum (26.11%) at temperature 316K and maximum value (27.04 %) is obtained at a temperature of 298 K.

Table: 4.4 Exegetic efficiency and Gas plant efficiency w.r.t. ambient temperature

T1[k]	η_{exer}	η_{GP}
298	0.327	0.2704
300	0.327	0.2704
302	0.3249	0.2693
304	0.3227	0.2681
306	0.3206	0.267
308	0.3184	0.2659
310	0.3161	0.2647
312	0.3138	0.2635
314	0.3115	0.2623
316	0.3092	0.2611

Variation of Exegetic efficiency, overall Efficiency and Steam plant efficiency w.r.t. boiler pressure are shown in table 4.5. Maximum value (32.7%) of exergetic efficiency was obtained at 40 bar and minimum value (32.3%) of at 58 bar. Maximum value (41.64%) of overall efficiency was obtained at 40 bar and minimum value (41.23%) of at 58 bar. Maximum value (40.34%) of steam plant efficiency was obtained at 58 bar and minimum value (38.83%) of at 40 bar.

Table: 4.5 Exegetic efficiency overall Efficiency and Steam plant efficiency w.r.t. boiler pressure

P_{boiler}	η_{exer}	$\eta_{overall}$	η_{SP}
40	0.327	0.4164	0.3883
42	0.3267	0.416	0.3903
44	0.3263	0.4156	0.3922
46	0.3259	0.4152	0.394
48	0.3256	0.4148	0.3958
50	0.3252	0.4144	0.3974
52	0.3248	0.4139	0.399
54	0.3244	0.4135	0.4006
56	0.324	0.413	0.402
58	0.3236	0.4126	0.4034

Variation of exergy loss in combustor, compressor, exhaust gases, HRSG and gas turbine with respect to pressure ratio is shown in table 4.6.

- Exergy loss is maximum for the combustor and it is increasing with the increase in pressure ratio in the combustor.
- Exergy loss for the compressor also increases with increase in pressure ratio and its minimum value achieved is at a pressure ratio-4.
- Exergy loss for the exhaust also increases with increase in pressure ratio and its minimum value achieved is at a pressure ratio-4.
- Exergy loss for the HRSG also decreases with increase in pressure ratio and its minimum value achieved is at a pressure ratio-13.
- Exergy loss for the gas turbine also increases with increase in pressure ratio and its minimum value achieved is at a pressure ratio-4.
- Exergetic efficiency also increases with increase in pressure ratio and its maximum achieved is at a pressure ratio-13.
- Exergetic efficiency of gas turbine also increases with increase in pressure ratio and its maximum value achieved is at a pressure ratio-13.

Table 4.6 Losses in various components w.r.t Pressure ratio

Rp	$\boldsymbol{I_{comb}}$	$\boldsymbol{I_{comp}}$	$\boldsymbol{I_{exh}}$	$\boldsymbol{I_{hrsg}}$	$\boldsymbol{W_{gt}}$	η_{exer}	$\boldsymbol{I_{gt}}$	η_{GP}
4	67750	2844	9265	9572	28812	0.3131	2298	0.202
5	73055	3852	11281	8998	35728	0.3213	3089	0.2276
6	78215	4925	13337	8538	42033	0.3256	3910	0.2461
7	83359	6076	15464	8160	47939	0.3272	4771	0.2599
8	88580	7317	17691	7847	53585	0.327	5681	0.2704
9	93955	8660	20043	7585	59073	0.3254	6651	0.2784
10	99555	10120	22547	7368	64484	0.3227	7691	0.2845
11	105450	11714	25232	7190	69886	0.319	8813	0.289
12	111712	13461	28131	7048	75341	0.3146	10031	0.2923
13	118423	15386	31280	6939	80913	2298	11359	0.2946

Variation of exergy loss in combustor, compressor, exhaust gases, HRSG steam turbine and gas turbine with respect to boiler pressure is shown in table 4.7. It is observed that With increase in boiler pressure Exergy loss is maximum for the combustor and it is increasing with the increase in boiler pressure in the combustor.

Table 4.7 Losses in various components w.r.t. boiler Pressure

P_{boiler}	I_{comb}	I_{comp}	I_{exh}	I_{gt}	I_{hrsg}	I_{ST}
40	88580	7317	17691	5681	7847	6267
42	89162	7365	18057	5719	7734	6291
44	89731	7412	18417	5755	7628	6314
46	90287	7458	18772	5791	7528	6335
48	90832	7503	19121	5826	7433	6355
50	91366	7547	19465	5860	7344	6373
52	91889	7590	19804	5893	7259	6391
54	92403	7632	20139	5926	7179	6407
56	92907	7674	20469	5959	7103	6422
58	93402	7715	20796	5960	7030	6436

Table 4.8 Variation in component w.r.t condenser pressure

$P_{condenser}$	η_{exer}	η_{SP}	$\eta_{overall}$
0.4	0.3378	0.296	0.3817
1.4	0.3435	0.2353	0.3589
2.4	0.346	0.2064	0.348
3.4	0.3477	0.1867	0.3406
4.4	0.3491	0.1715	0.3349
5.4	0.3501	0.159	0.3302
6.4	0.351	0.1482	0.3261
7.4	0.3517	0.1386	0.3225
8.4	0.3523	0.1299	0.3192
9.4	0.3528	0.122	0.3163

Variation of Exegetic efficiency, steam plant and overall efficiency with respect to condenser pressure is shown in table 4.8. It is observed that with increase in condenser pressure the Exegetic efficiency increase and maximum value is 35.28% and the steam plant efficiency is decreased with increasing the condenser pressure, overall efficiency also decrease.

Variation of Exegetic efficiency, exergy loss in combustion chamber with respect to pressure drop is shown in table 4.9.

Table 4.9 Variation in component w.r.t Pressure drop

P_{drop}	$\boldsymbol{I_{comb}}$	$\boldsymbol{I_{GT}}$	$\boldsymbol{W_{gt}}$	$\eta_{\boldsymbol{exer}}$	$\eta_{\boldsymbol{GP}}$	P drop CC
2	89088	5759	54583	0.3286	0.2731	0.16
3	88580	5681	53585	0.327	0.2704	0.24
4	88073	5604	52592	0.3254	0.2676	0.32
5	87567	5527	51604	0.3238	0.2648	0.4
6	87064	5451	50619	0.3221	0.262	0.48
7	86561	5375	49639	0.3204	0.2592	0.56
8	86061	5299	48662	0.3187	0.2563	0.64
9	85561	5224	47690	0.317	0.2533	0.72
10	85063	5149	46721	0.3153	0.2504	0.8
11	84567	5074	45757	0.3135	0.2474	0.88

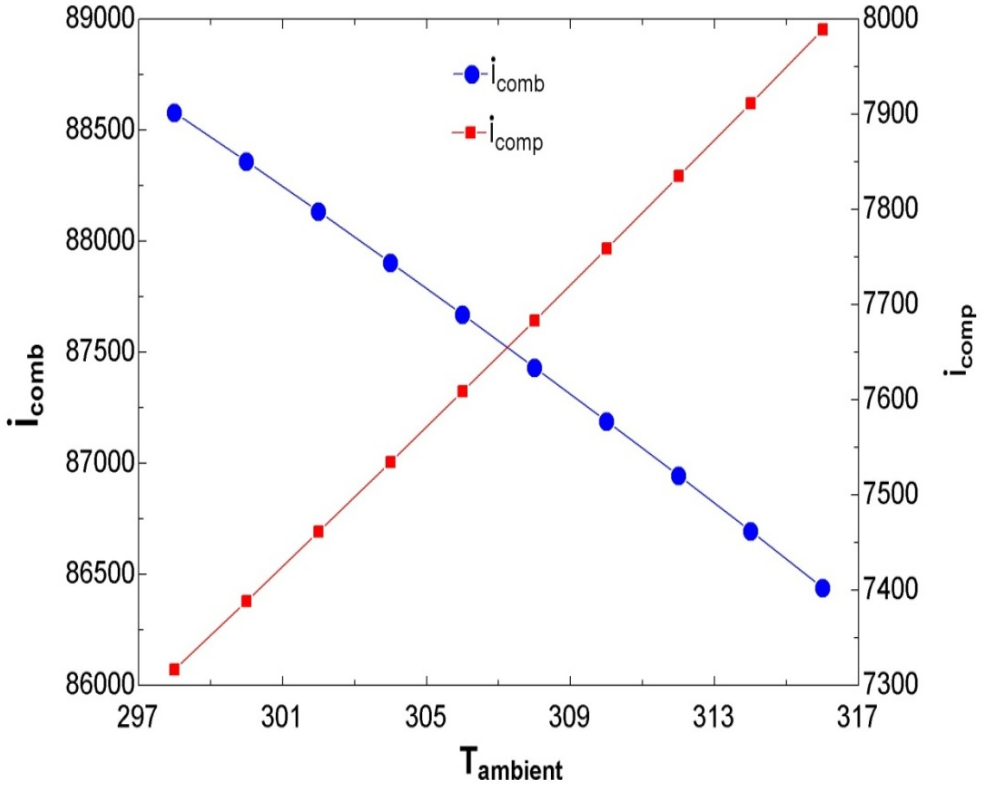

Figure: 4.2 Exergy loss (combustor and compressor) v/s ambient temperatures

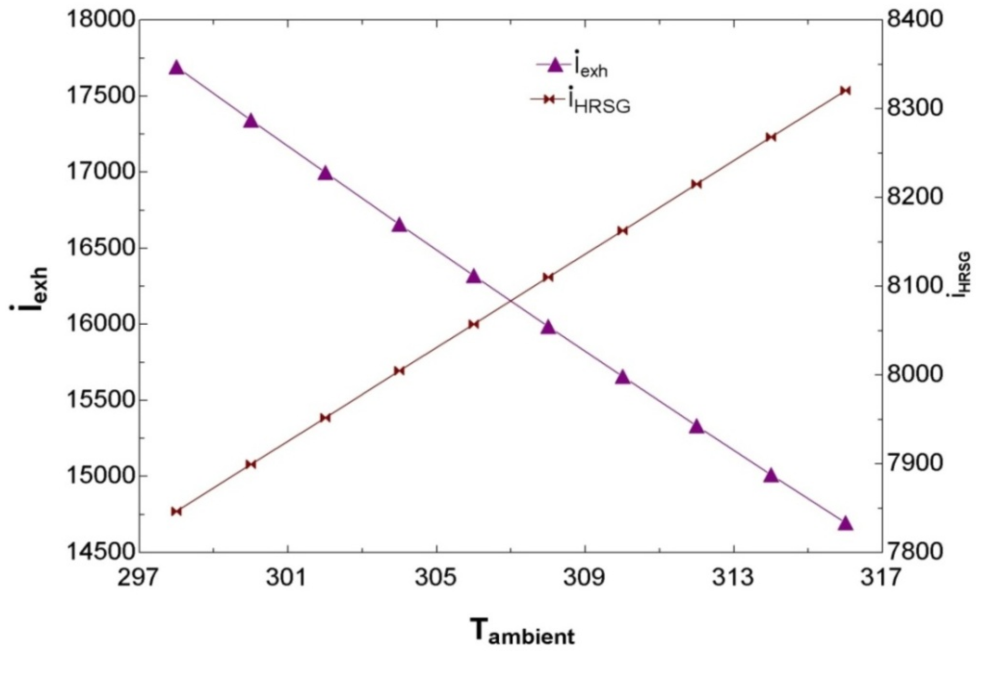

Figure:4.3 Exergy loss (exhaust and HRSG) v/s ambient temperatures

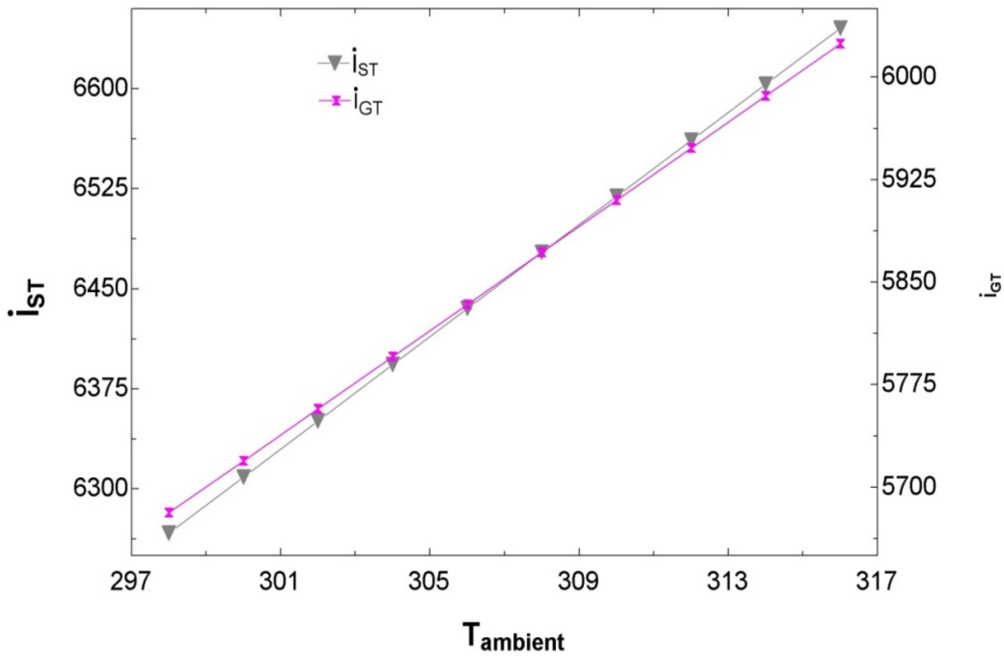

Fig: 4.4 Exergy loss (steam turbine and gas turbine) v/s ambient temperature

In the Figure 4.2 the irreversibility or exergy loss in combustor is decreasing with the variation of ambient temperature in the range 298 to 316 K and in compressor exergy loss increasing.

In the Figure 4.3 the rate of Exergy dissipation in the heat recovery steam generator is increasing with increasing the ambient temperature and exhaust loss due to flue gases is decreasing.

In Figure 4.4 Rate of Exergy dissipation in the steam turbine or lost work is increasing with increasing the ambient temperature and lost work in gas turbine is slightly less with increasing the ambient temperature.

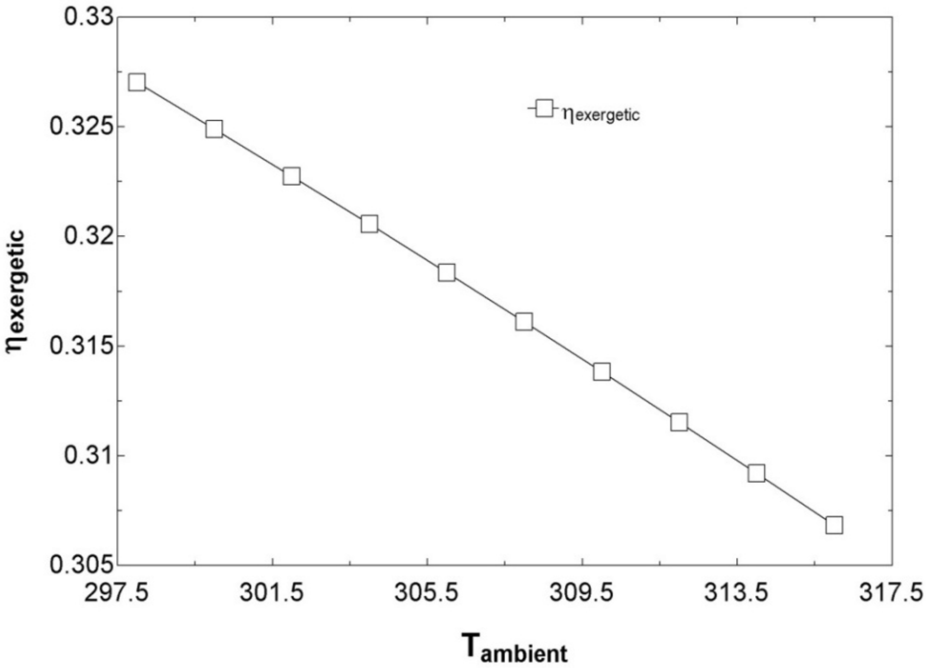

Fig: 4.5 Exergetic efficiency v/s ambient temperature

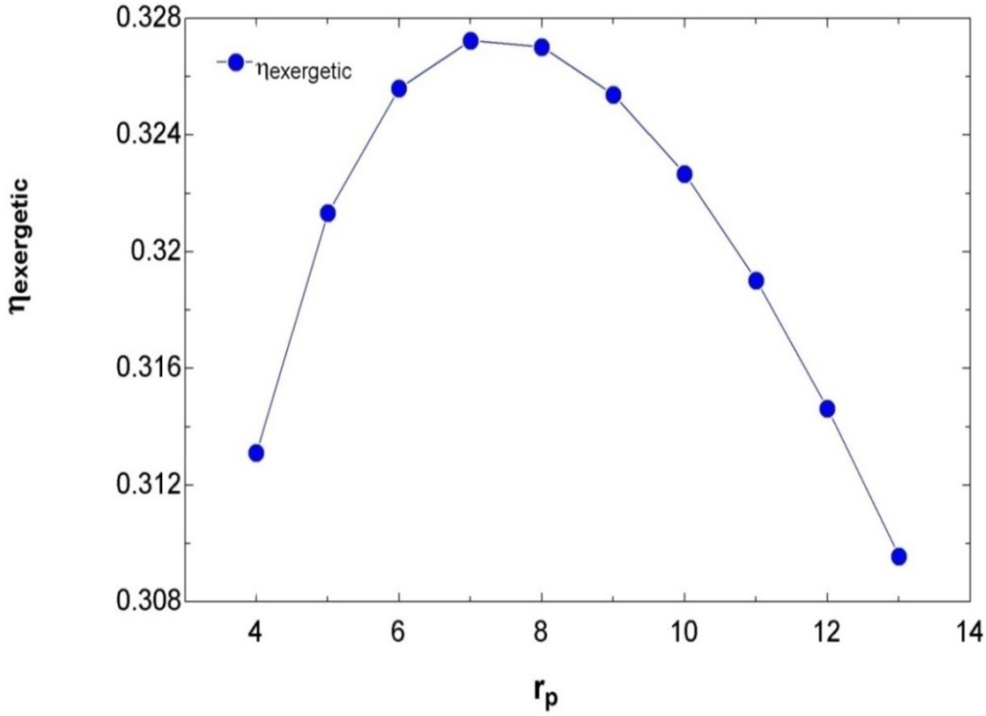

Fig: 4.6 Exergetic efficiency v/s pressure ratio

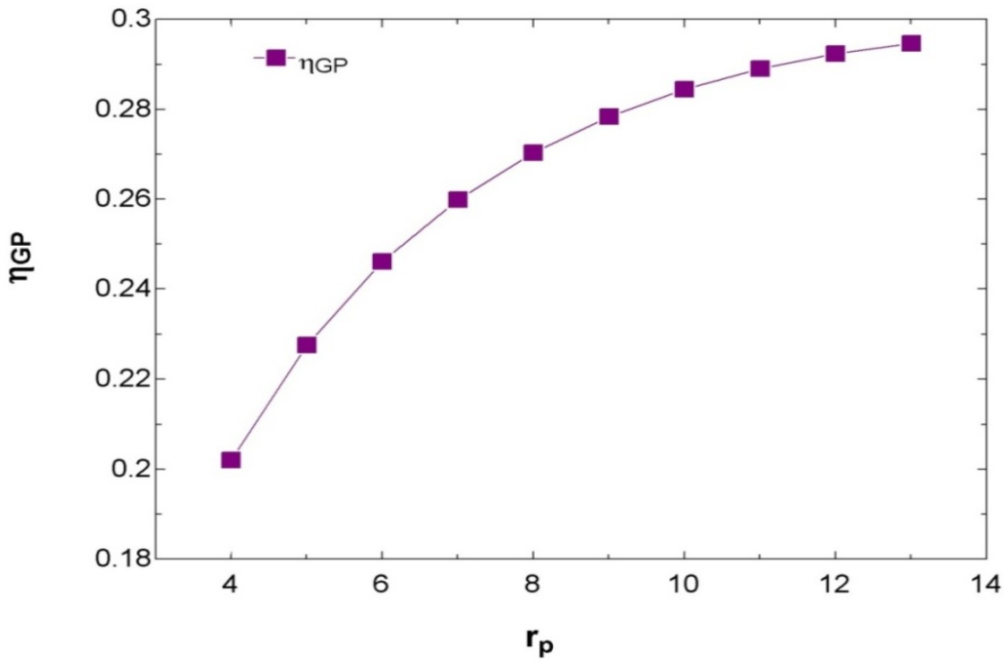

Fig: 4.7 Efficiency (gas plant) v/s Pressure ratio

In Fig. 4.5 Exergetic efficiency is decreasing with increasing ambient temperature, because the condenser pressure would be higher at higher ambient temperature. Hence the condenser saturation temperature would also be higher. So at higher ambient temperature efficiency will be low.

In the Fig. 4.6 Exergetic efficiency firstly increase with increasing pressure ratio and have maximum value at pressure ratio (7.5) approximate. And further increasing the pressure ratio Exergetic efficiency is decreasing

In Fig 4.7 Efficiency of gas plant is increases with increase in pressure ratio, but after pressure ratio = 12 rate of increase of efficiency w.r.t. pressure ratio is very less i.e. it is nearly constant (30% maximum).

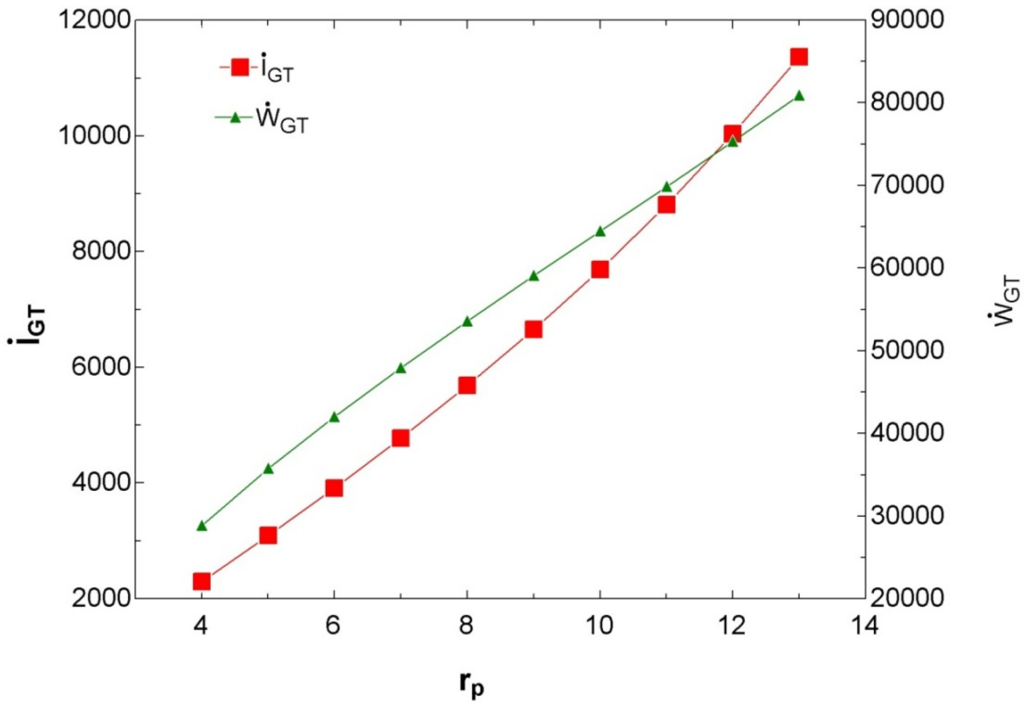

Fig: 4.8 Exergy losses in Gas turbine and power output (GT) v/s pressure ratio

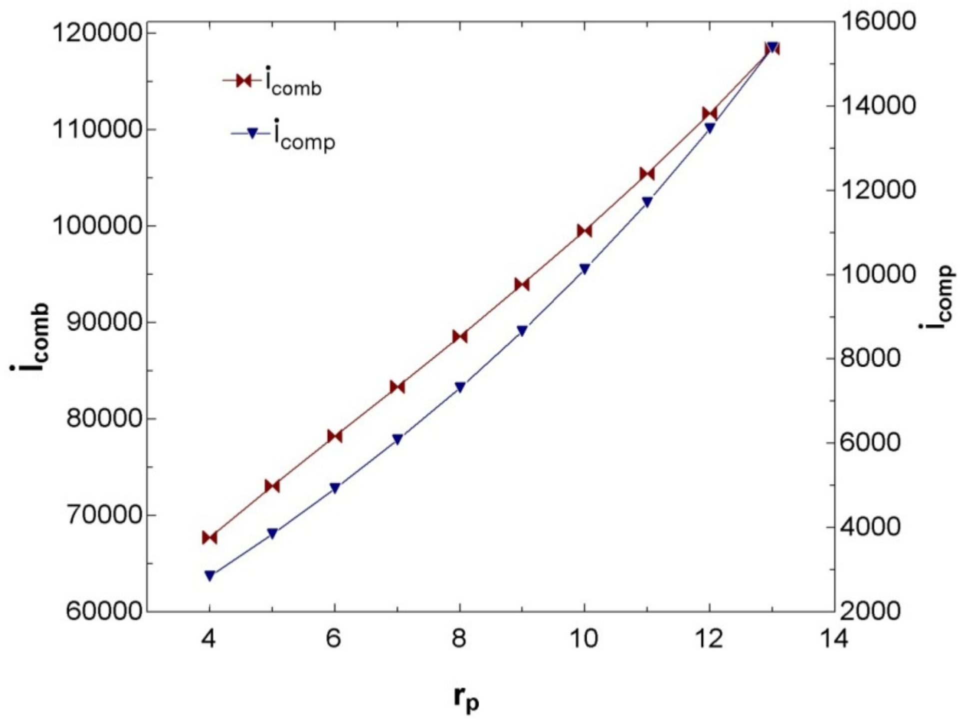

Fig :4.9 Exergetic loss in combustor and compressor v/s pressure ratio

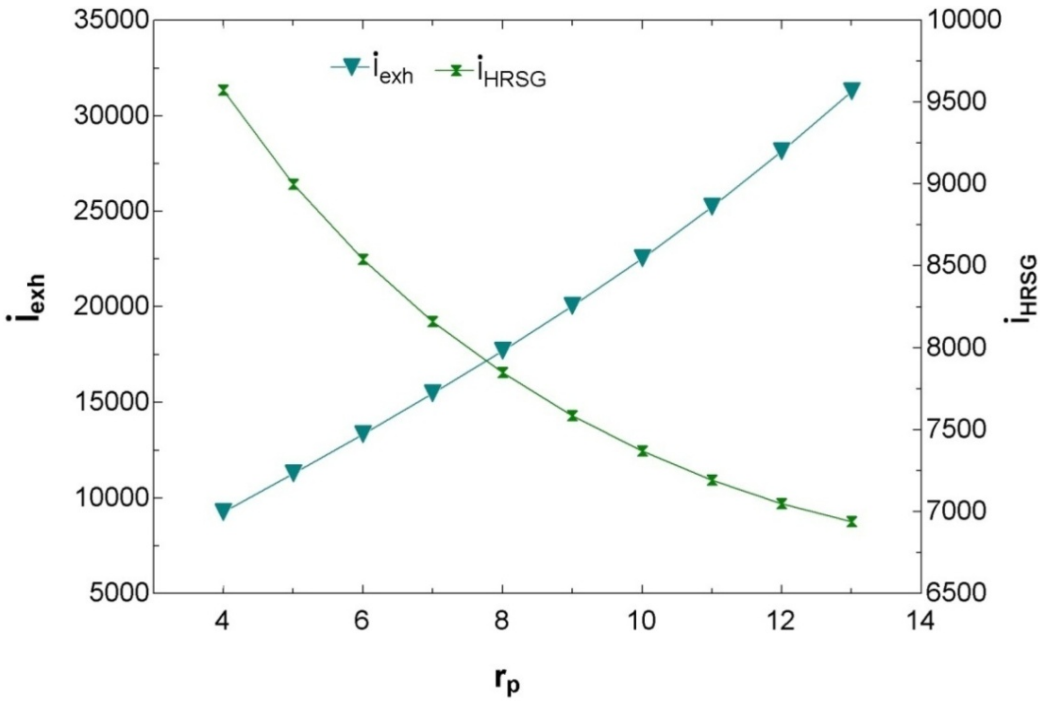

Figure: 4.10 Exergy loss (exhaust gases) v/s pressure ratio

In Figure 4.8 Exergy loss or irreversibility in gas turbine increasing with increase in pressure ratio and in gas turbine output also increase with increasing the pressure ratio.

In Figure 4.9 Exergy losses in combustor and compressor is increasing with increasing pressure ratio. Again, the behaviour of the intermediate section is following the same trend. This is due to highest temp of the working fluid, chemical reactions and a small pressure drop.

In the Figure 4.10 Exergy loss in Exhaust gases is increases with increasing pressure ratio, while in HRSG there is a decrease in exergy loss is observed with increase in pressure ratio.

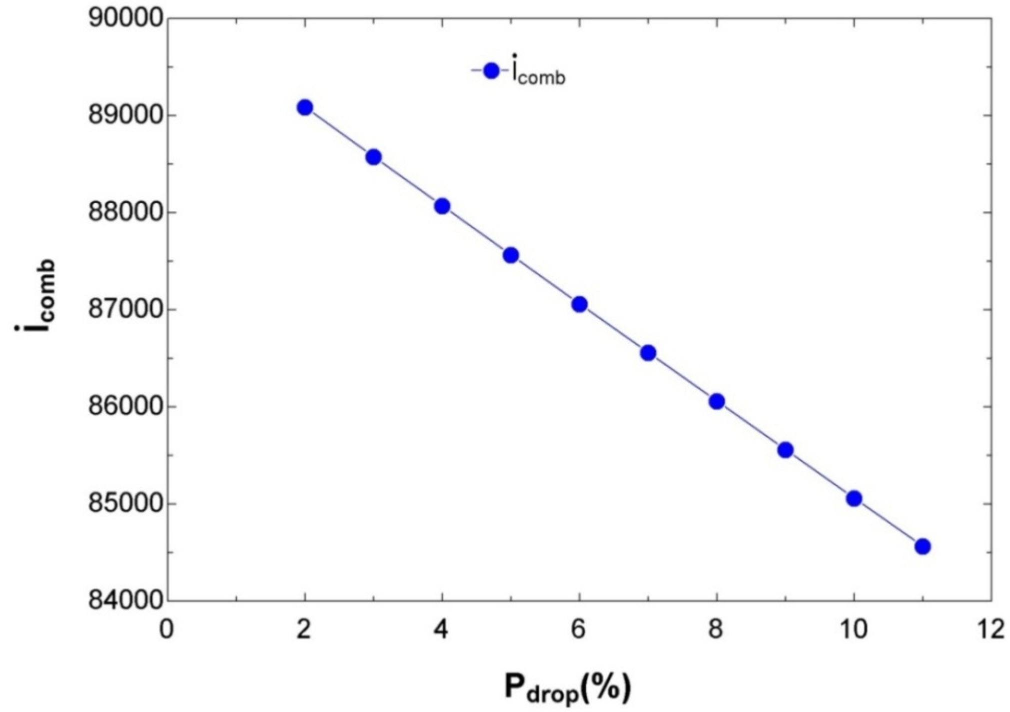

Figure: 4.11 Exergy loss combustor) v/s pressure drop

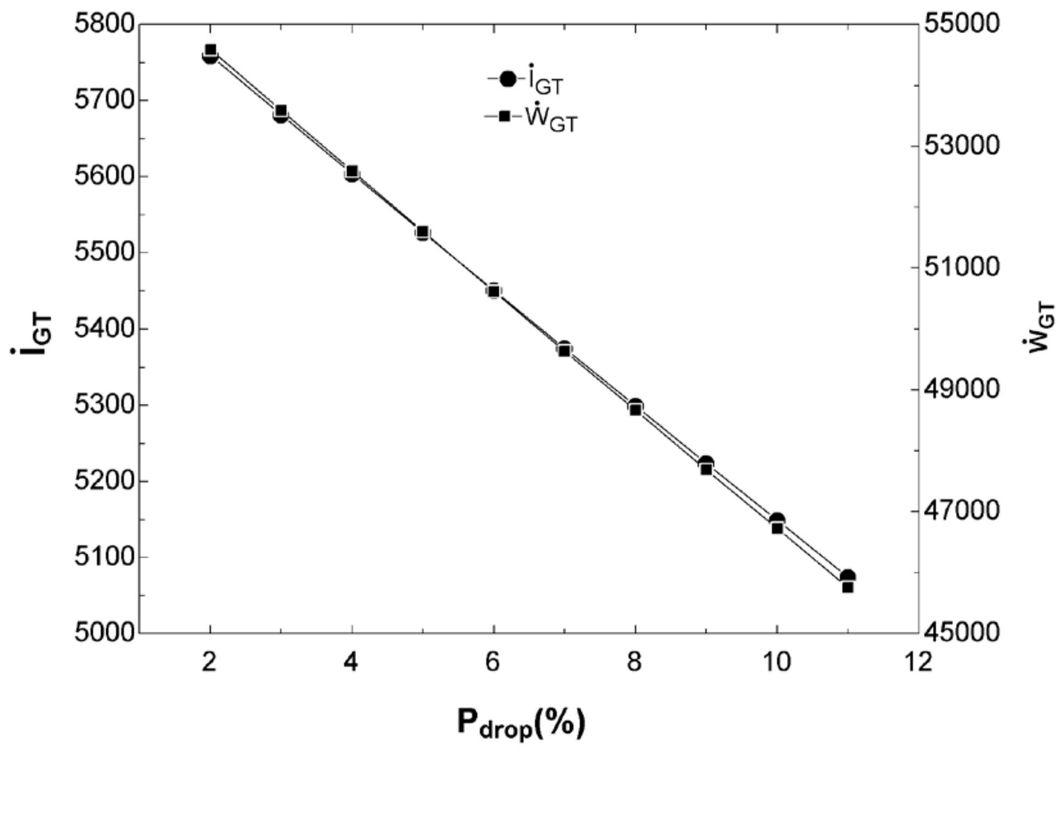

Figure: 4.12 Exergy loss (GT) v/s pressure drop

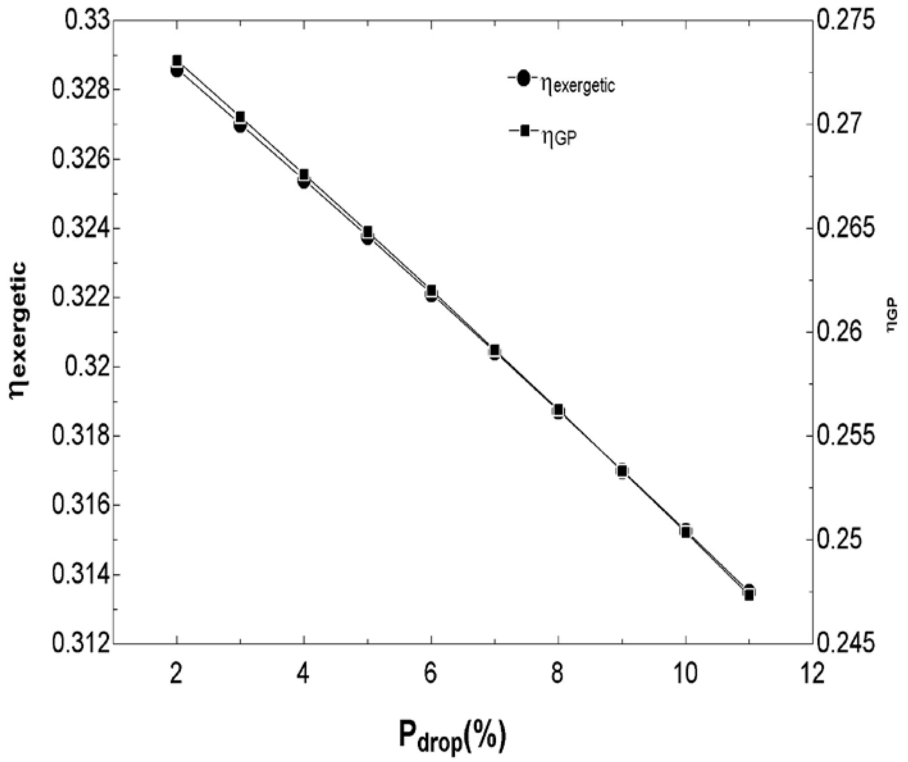

Figure : 4.13 Exergetic efficiency and gas plant efficiency v/s pressure drop

In the Figure 4.11. Exergy loss in combustor is decreasing linearly with increase in pressure drop.

In the Figure4.12 Exergy loss in gas turbine and output of gas turbine both follow linear relation with variation in pressure drop. Exergy loss in gas turbine decreases with increase in pressure drop and output of the gas turbine also decreases with increase in pressure drop.

In the Figure 4.13 Exergetic efficiency decreases with increase in pressure drop and gas power plant efficiency is decreasing with increase in pressure drop.

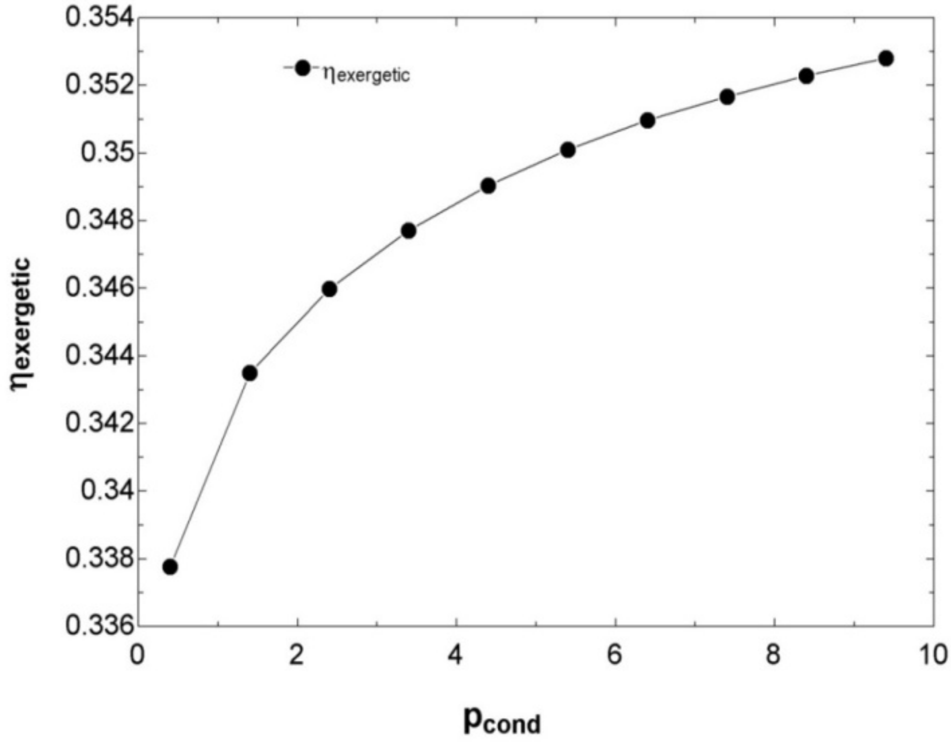

Figure: 4.14 Exergetic efficiency v/s Condenser pressure

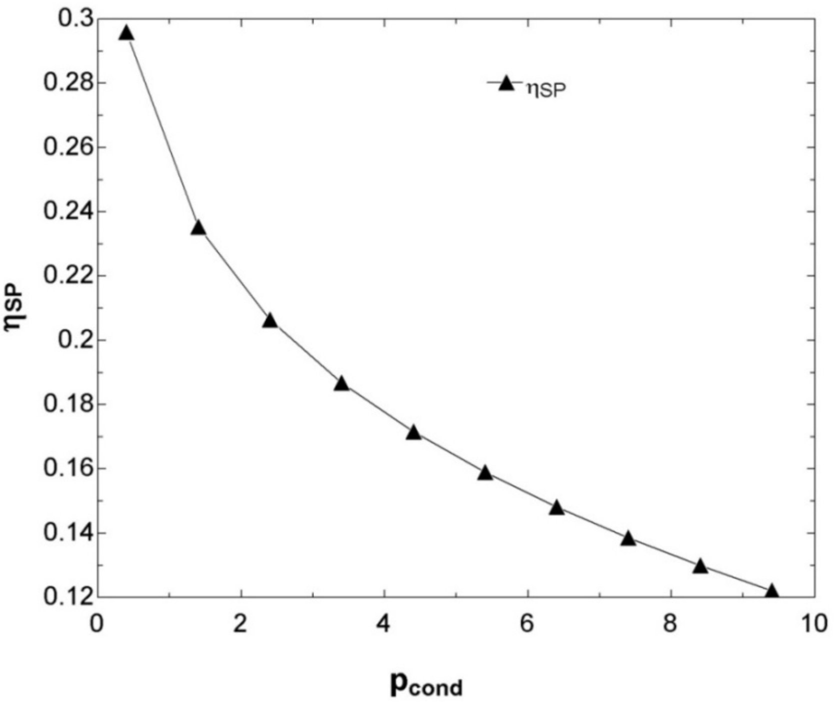

Figure :4.15 Exergetic efficiency(SP) v/s Condenser pressure

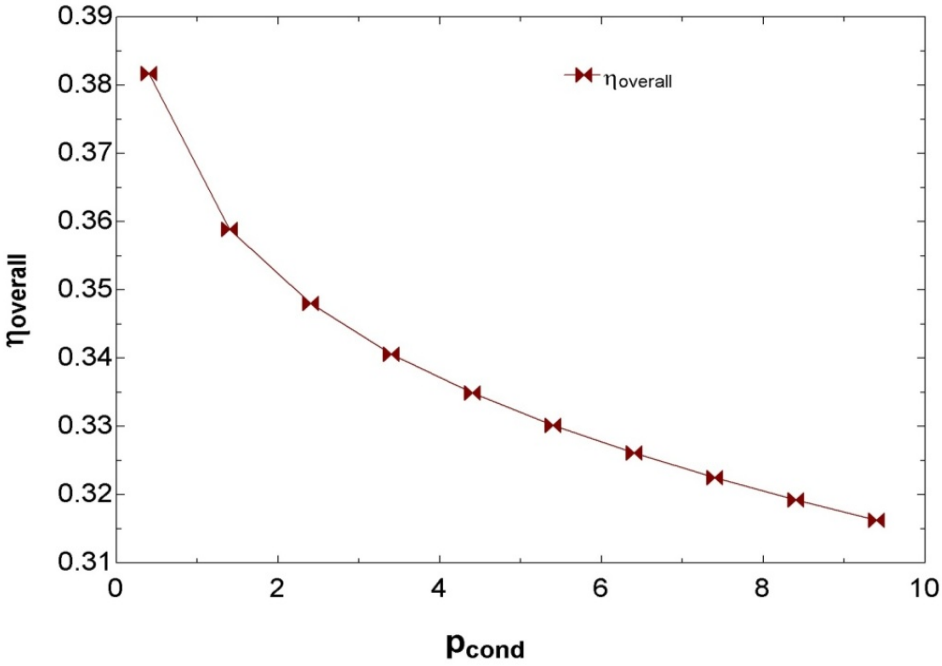

Figure :4.16 Overall efficiency(plant) v/s Condenser pressure

In Fig. 4.14 indicates the variation of exergetic efficiency plant w.r.t. condenser pressure. Exergetic efficiency is increases with increases in condenser pressure. At lower pressure it increases at faster rate as compared to increasing rate at higher pressure.

In Figure 4.15 indicates the variation of efficiency of steam power plant w.r.t. condenser pressure. Exergetic Efficiency of steam plant is decreasing with increase in condenser pressure.

In Figure 4.16 indicates the variation of overall efficiency of plant w.r.t. condenser pressure. Overall efficiency of the plant decreasing with Increase in condenser pressure.

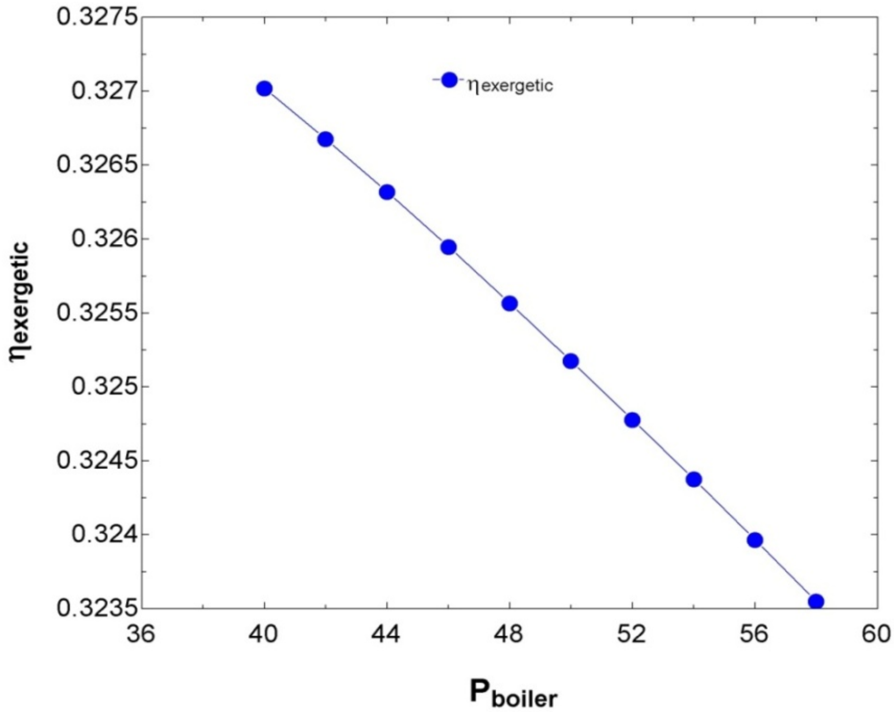

Figure: 4.17 Exergetic efficiency v/s Boiler pressure

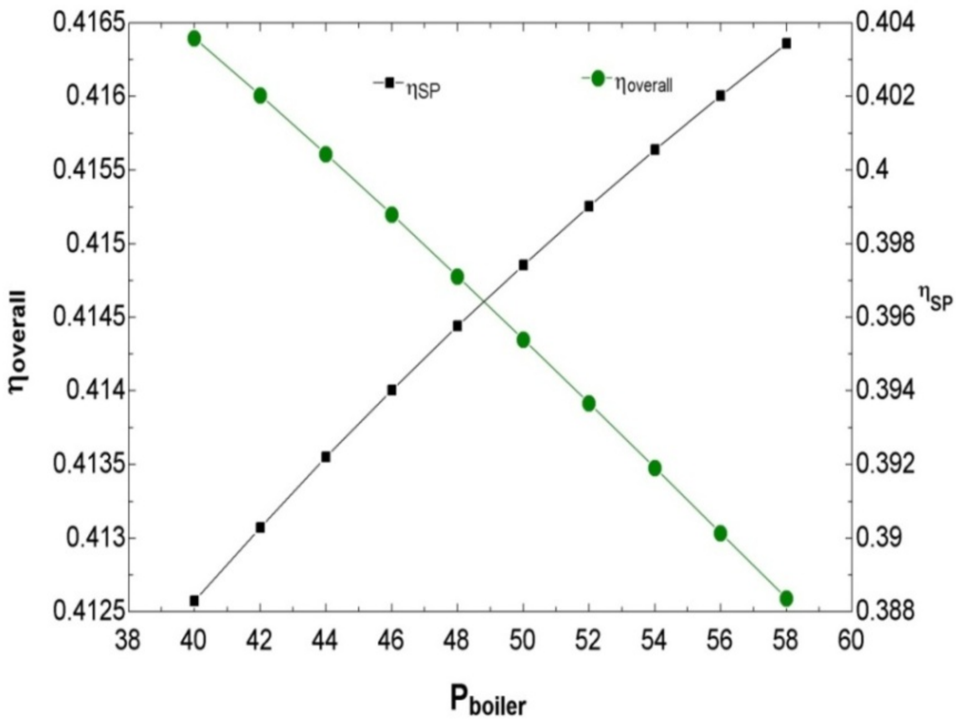

Figure: 4.18 Overall efficiency v/s Boiler pressure

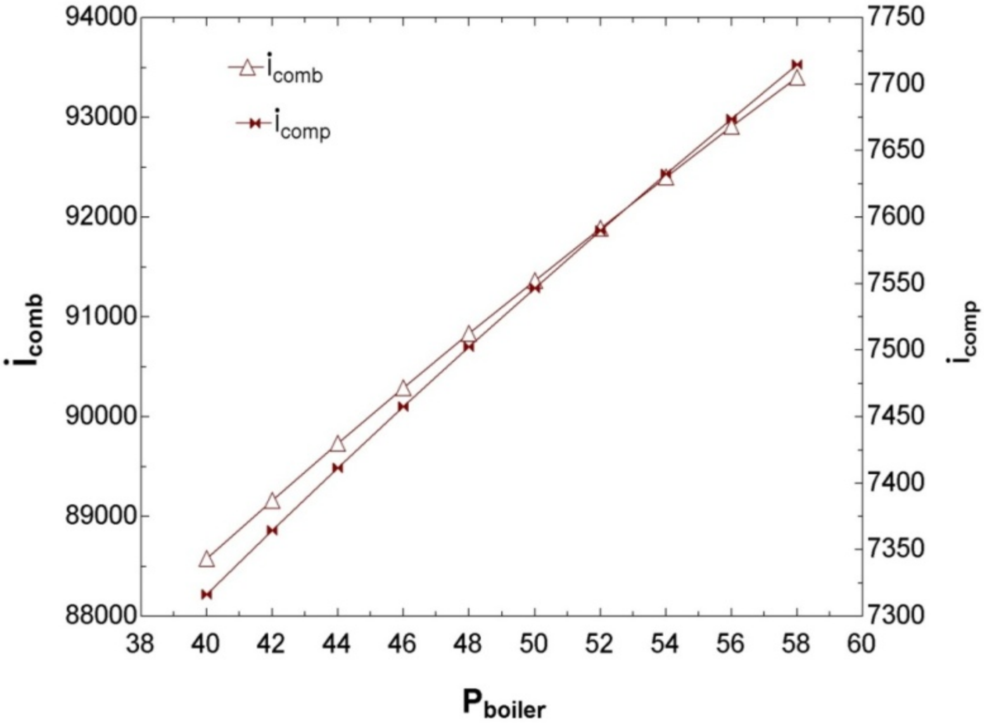

Figure: 4.19 Exergy dissipation in combustor and compressor v/s condenser pressure

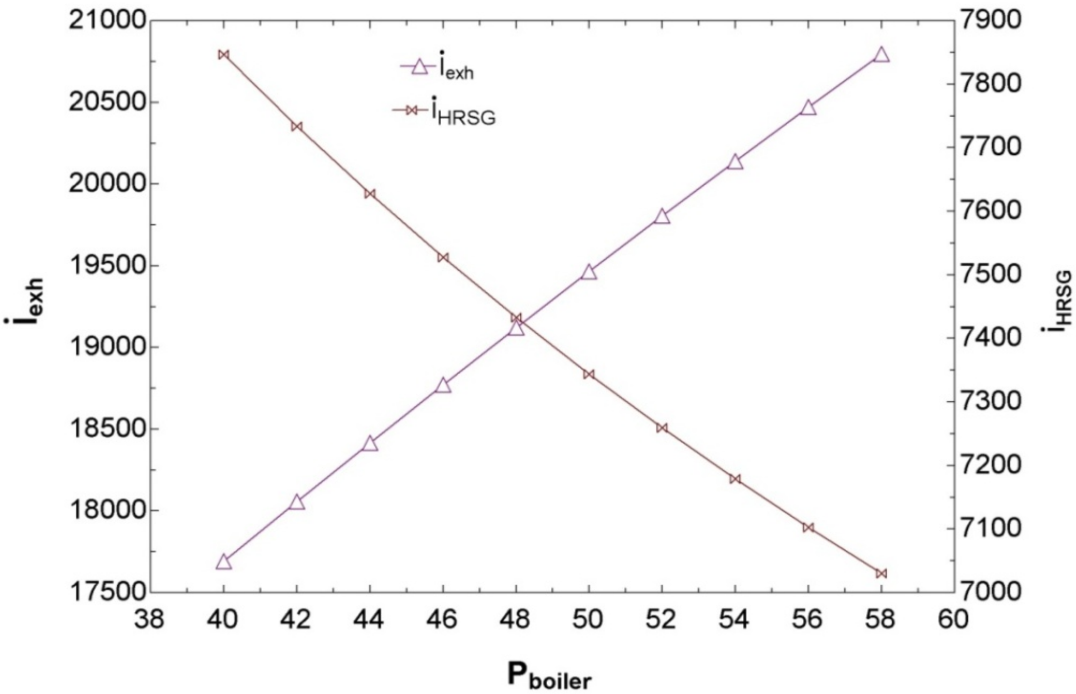

Figure: 4.20 Exergy dissipation in combustor and compressor v/s Boiler pressure

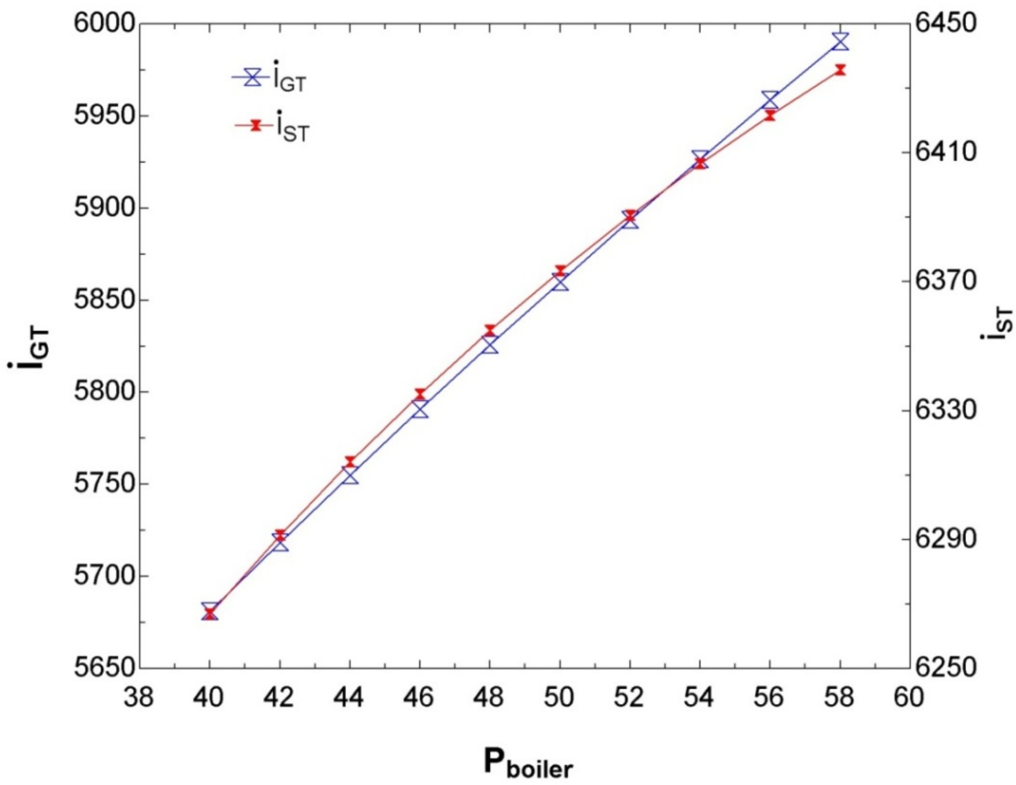

Figure: 4.21 Exergy dissipation in GT and ST v/s Boiler pressure

In Figure 4.17 Exegetic efficiency decreases with increase in boiler pressure and maximum Exergetic Efficiency achieved at 32.77 at boiler pressure 40bar.

In Figure 4.18 Overall efficiency decreases with increase in boiler pressure and at 40 bar maximum efficiency 41.05.

In Figure 4.19 exergy loss in combustor and compressor is increasing with increasing the boiler pressure.

In Figure 4.20 the Exergy dissipation is increasing with increasing the boiler pressure in the exhaust gases.

In Figure 4.21 Exergy dissipation in steam turbine and gas turbine dissipation is increasing with increasing the boiler pressure.

CHAPTER-5
CONCLUSION

During this extensive energy and exergy analysis of combined cycle following conclusions are summarized below:

- Exergy analysis is presented in this thesis to be able to help understand the performance of combined cycle.
- It provides us a systematic process for production the maximum power .By the exergy analysis we can conclude that main exergy loss occurs in the in the boiler in steam power plant and in combustion chamber in the gas power plant.
- Low cycle efficiency, due to the large exhaust loss, large compressor work and other parameters.
- The principle of increasing efficiency in the combined cycle power plant is related to the increase of the mean temperature of the heat supply and the decrease of mean temperature of heat rejection.
- For higher compressor pressure ratio, the compressor exit temperature increases. Thus, for a specified turbine entry temperature, the exergy destruction inside the combustor decreases.
- The major energy destruction occurs in the heat recovery system which leads to inefficient heat transfer between hot stream (flue gas) and cold stream (water & air)
- It has been found that maximum exergy loss occur in combustor (furnace) which shows combustor is not fully adiabatic and combustion may not be complete. It is due to the irreversibility within the combustion process. This study pin points that the combustor requires necessary modification like refractory (insulation) modification to reduce exergy destructions thereby plant performance can be improved.

5.1 Validation: I found that the maximum exergy losses occurred in the combustion chamber and minimum exergy loss occurred in gas turbine, which are in line with the review from the literature.

5.2 Further scope of research: This work will identify major sources of losses and exergy destruction in the power plant. It will provide ways and means to improve the system performance and reduce environment impact. Finally, it will perform a parametric study to determine how the system performance varies with different operating parameters.

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