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Exergy Assessment of Major Components in a Dual Cycle Power Plant Featuring an Organic Rankine Cycle and Absorption Refrigeration System

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ABSTRACT

An integrated combined cycle power plant's (ICCPP) energy and exergy analysis is presented in this thesis, with an emphasis on improving efficiency and reducing environmental effect. The project investigates the integration of low-grade energy recovery devices for extra power generation and cooling using exhaust gases, such as the “Organic Rankine Cycle (ORC)” and absorption refrigeration. According to the investigation, the compressor inlet temperature is a critical factor in overall efficiency, and the combustion chamber and heat recovery systems account for the majority of exergy losses”. The study pinpoints important areas for improvement, such as combustor and heat recovery system optimization to lower energy losses, by doing a thorough exergy analysis. The thesis concludes by suggesting future research directions, including parametric analysis, integration with renewable energy sources, and the development of advanced control strategies to further enhance the performance and sustainability of ICCPPs. The findings are validated through comparison with existing literature.

Keywords— **ICCPP: Integrated Combined Cycle Power Plant, ORC: Organic Rankine Cycle, CCPP: Combined Cycle Power Plant, HRSG: Heat Recovery Steam Generator, VAM: Vapor Absorption Machine**

1. Introduction

1.1 Global Energy Demand and Challenges Population Growth and Economic Development

Impact of Population Growth:

The last few decades have seen a sharp increase in the world's population. The world's population is expected to surpass 8 billion by 2024, with substantial growth anticipated in poorer nations. The increasing number of people requiring power for everyday needs including lighting, heating, cooling, transportation, and industrial operations puts tremendous strain on energy resources. For instance, the United Nations projects that by 2050, there will be 9.7 billion people on the planet”, increasing the need for energy.

Economic Development and Energy Consumption:

Another major factor influencing the need for energy is economic growth. Energy consumption rises when economies grow because of the acceleration of industrialization and urbanization. Emerging economies are consuming a lot more energy as a result of the fast industrial growth they are experiencing, especially in Asia and Africa. For example, as their industrial and service sectors grow, India and China, two of the fastest-growing economies, have witnessed significant increases in their energy consumption. The International Energy Agency's (IEA) prediction that, if current trends continue, global energy demand might climb by 25% by 2040 reflects this tendency.

Statistics and Projections:

The International Energy Agency (IEA) projects a 6% yearly growth in global energy demand in its World Energy Outlook 2023. Increased economic activity, rising living standards, and a growing population are all factors contributing to the rise in energy consumption. Furthermore, the Global Energy Statistical Yearbook 2024 shows that during the past ten years, the amount of electricity consumed globally has increased by about 4% annually, indicating a growing dependence on electrical energy.

1.2. Environmental Concerns

Air and Water Pollution:

The generation of energy, especially from fossil fuels, is a significant contributor to pollution in the air and water. Pollutants as “sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter are released into the atmosphere during the combustion of coal, oil, and natural gas. These pollutants have a negative impact on public health and are a contributing factor to respiratory and cardiovascular disorders. Furthermore, spills and runoff from the extraction and transportation of fossil fuels have the potential to contaminate water, harming aquatic ecosystems and sources of” potable water.

“Greenhouse Gas Emissions:

The generation of energy from fossil fuels contributes significantly to greenhouse gas (GHG) emissions, which are the primary cause of climate change. More than 70% of all greenhouse gas emissions come from energy-related activities. These emissions include carbon dioxide (CO_2). Global CO2 emissions have risen by more than 40% since 1990, according to the Intergovernmental Panel on Climate Change (IPCC), which has exacerbated global warming” and increased the frequency and severity of climate extremes including heatwaves, storms, and droughts.

Climate Change:

Ecosystems, agriculture, and human settlements are all seriously at risk from climate change brought on by growing greenhouse gas emissions. Sea levels are rising due to the melting of ice caps brought on by rising global temperatures, endangering coastal populations. There is an “increasing frequency of extreme weather events that affect water supplies, agriculture, and infrastructure. In order to alleviate the effects of climate change on the environment and reduce carbon footprints, a shift toward cleaner energy sources and increased” energy efficiency is necessary.

1.3. Energy Market Instability

Geopolitical Tensions:

Geopolitical conflicts can cause price volatility and supply chain disruptions, which can have a substantial impact on the energy markets. Conflicts in oil-producing countries, like the Middle East, have the potential to impact energy security and cause swings in the price of oil globally. For instance, delays in oil production and export have been caused by political unrest in Venezuela and Iran, which has affected the world's energy markets and oil prices.

Resource Scarcity:

The generation of energy is hampered by resource scarcity, which is caused by the depletion of fossil fuel reserves and the restricted availability of essential raw materials. Because fossil fuels are limited, when reserves are depleted, the cost of extraction rises, pushing up the price of energy. Furthermore, the development of these industries may be hampered by the lack of certain resources needed for renewable energy technologies, such as rare earth elements for solar panels and wind turbines.

Economic Crises:

Economic downturns, like the world financial crisis in 2008, can result in a decrease in investments in energy-related innovation and infrastructure. Energy demand and prices are impacted by economic instability since lower economic activity can result in lower energy consumption and lower investment in energy projects. For example, during the COVID-19 pandemic, a decrease in industrial output and travel restrictions resulted in a decrease in energy consumption, which caused notable swings in energy costs.

In summary, tackling the issues posed by the world's energy consumption calls for a diverse strategy that includes improving energy efficiency, creating sustainable energy sources, and developing cutting-edge technology to lessen “their negative effects on the environment and stabilize the energy markets. Policymakers and stakeholders can work toward building a more resilient and sustainable energy future” by understanding the interactions between population increase, economic development, environmental concerns, and market dynamics.

1.4. Cogeneration Systems and Efficiency

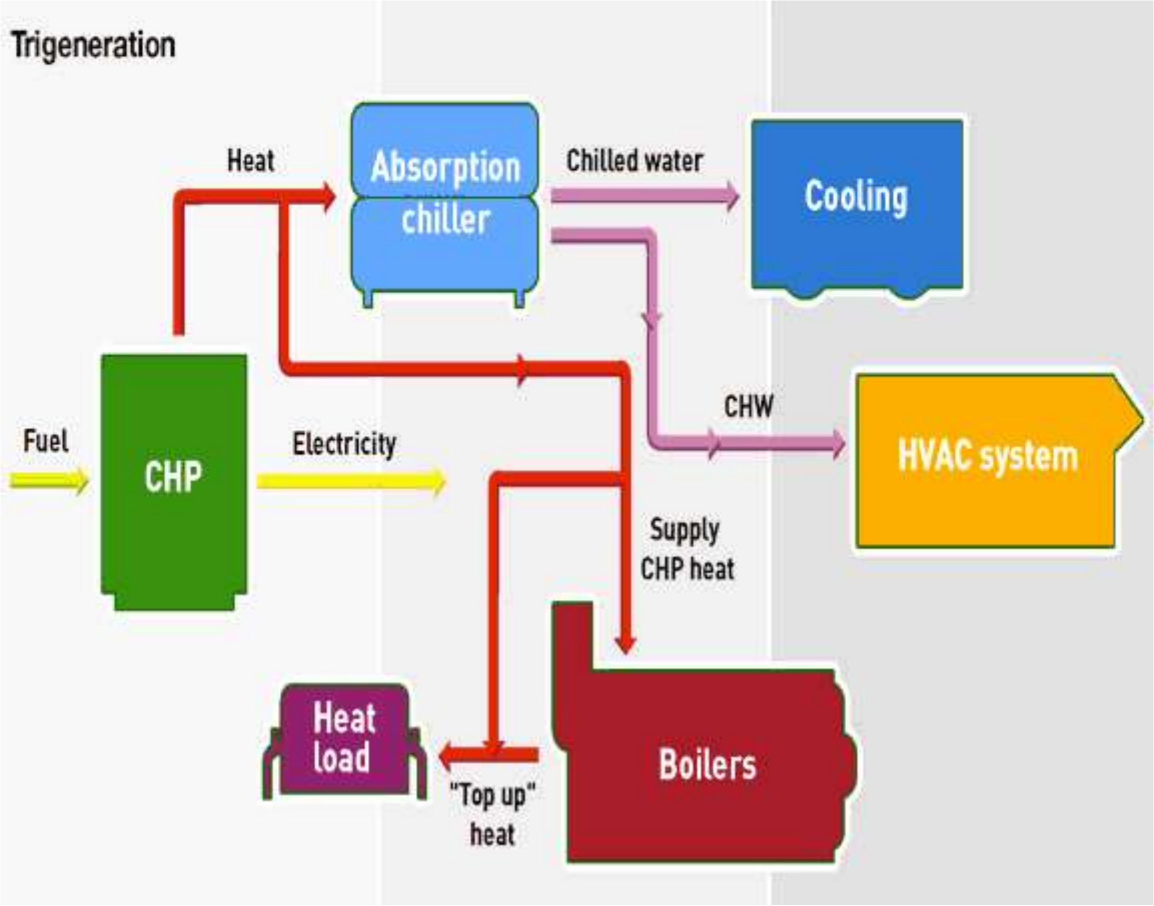

Fig No 1 Cogeneration System and Efficiency

1.4.1 Principles of Cogeneration

“Cogeneration is the process of simultaneously producing electricity and useable heat from the same energy source. It is often referred to as combined heat and power (CHP)”. In contrast to traditional power plants, which only produce electricity and discharge any leftover heat into the atmosphere, cogeneration systems absorb and use waste heat for other uses, such industrial processes or building heating. This twofold energy generation raises the power plant's total efficiency.

The Operation of Cogeneration:

- “Primary Energy Source: Natural gas, coal, biomass, or waste” heat are just a few of the primary energy sources that cogeneration systems use.
- Electricity Generation: To produce electricity, the main energy source is burned in a turbine or engine.
- Heat Recovery: “A heat recovery steam generator (HRSG) or a comparable apparatus is used to collect the waste heat generated during the production” of electricity.
- Heat Utilization: By using the recovered heat for processes like hot water generation, district heating, or industrial operations, the system's total energy efficiency is raised.
- Part in Increasing Power Plant Efficiency: Cogeneration systems have an efficiency of 70–90%, while traditional power plants have an efficiency of 30–40%. Cogeneration lowers fuel usage and greenhouse gas emissions while simultaneously increasing energy output by harnessing waste heat that would otherwise be lost.

1.5. OBJECTIVE OF PRESENT WORK

Research Objectives

Outline of Objectives:

- **Primary Goals:** Clearly state the precise goals of the research, such as increasing the efficiency of power plants, analyzing cogeneration systems, or gauging the effects of renewable energy technology.
- **Techniques:** Give an overview of the research's methods and tools, such as case studies, simulation models, and data analysis strategies.

1.6. Scope and Limitations

Scope of the Study:

- **Focus Areas:** Specify the parameters of the research, such as the elements of power plants or energy systems under examination.
- **Limitations:** Recognize any limits or restrictions, such as regional restrictions or particular technology under investigation.

Limitations:

- **Data Availability:** Limitations related to the availability and accuracy of data used in the research.
- **Scope Constraints:** Challenges in addressing all aspects of the research topic due to time, resources, or scope constraints.

1.7 Expected Outcomes

Potential Outcomes:

- **Insights and Recommendations:** Discuss the potential outcomes of the research, such as recommendations for improving power plant efficiency, policy implications, or technological advancements.
- **Implications for the Power Sector:** Explore the implications of the research findings for the power sector, including potential benefits for energy efficiency, sustainability, and economic performance.

2. Literature review

Based on the past researchers paper, web site, various structural codes ,books and journals are presented in this section.

(I.H. Njoku, 2018) In order “to improve energy efficiency and environmental sustainability, the integration of Organic Rankine Cycle (ORC) and Absorption Refrigeration Cycle (ARC) with Combined Cycle Power Plants (CCPP) has been thoroughly studied in the literature. Previous studies have shown the potential of ORC systems, which increase plant efficiency by generating additional energy from low-grade waste heat. Optimizing energy recovery in ORC has been very successful when using working fluids like R113. Similar to this, ARC systems have been used to lower the temperature of the intake air in gas turbines”, increasing power output and particularly useful in hot areas. One important method used in these investigations is exergy analysis, which has given thorough insights into the efficiency gains and exergy destruction reduction possible with these kinds of integrations. Furthermore, evaluations of the sustainability index have emphasized the advantages these integrated systems have for the environment, emphasizing their capacity to cut emissions and fuel use. Expanding upon previous research, this study provides a thorough assessment of the environmental benefits and performance gains by statistically analyzing the energy, exergy, and sustainability consequences of integrating ORC and ARC with a CCPP in a tropical setting.

(O Pektezel, 2019) Different working fluids and system configurations have been widely studied in the literature on “energy and exergy analysis of vapor compression refrigeration cycles linked with Organic Rankine Cycles (ORC) to determine their overall impact on efficiency. Research has indicated that the selection of suitable working fluids, such R600a, can greatly improve system performance. It is important to take into account the global warming potential (GWP) and ozone depletion potential (ODP) of these fluids. Studies have also demonstrated how crucial it is to enhance COP (coefficient of performance) and exergy efficiency (ηex) by optimizing parameters such as evaporator and condenser temperatures, as well as turbine and compressor isentropic efficiencies.

(Navid Nazari, 2021) Recent developments in hybrid energy systems have looked into combining direct combustion biomass and solar pre-heating technologies to improve power, heating, and cooling production efficiency. A noteworthy study put forth a unique configuration that combines a “Li-Br/H2O absorption refrigeration cycle, a trans-critical organic Rankine cycle (ORC), and an externally driven gas turbine. Through the lenses of energy, exergy, and exergo-economic analysis”, this system was found to have significantly improved. With a noteworthy 6% decrease in the product cost rate, the energy efficiency rose to 55.56% and the energy efficiency to 20.38%. This hybrid technique produced around 10% more energy efficiency than standard systems. A multi-objective optimization algorithm called MOMVO was used in the study. It performed better than conventional techniques, offering a 9% gain in energy efficiency at the same time as cost savings. This demonstrates how advanced optimization approaches and integrated systems can enhance the efficiency and financial sustainability of energy systems.

(Shahab Yousefizadeh Dibazar, 2020) **V**arious configurations of Organic Rankine Cycles (ORCs) have been studied recently in order to prevent energy destruction and increase energy efficiency. Using both conventional and sophisticated exergy studies, this study compared three forms of “ORCs: basic ORC (BORC), ORC with single regeneration (SRORC), and ORC with double regeneration (DRORC). While advanced exergy analysis offers deeper insights by classifying exergy destruction into avoidable, unavoidable, endogenous, and exogenous elements, conventional exergy analysis evaluates component performance in isolation. The findings show that when it comes to lowering irreversibilities, regenerative ORCs (SRORC and DRORC) perform noticeably better than BORC. For example, in avoidable/endogenous sections, SRORC and DRORC show noteworthy exergy destruction rates of 4.13 kW and 5.25 kW, respectively. Turbines, evaporators, condensers, and feed-water heaters are identified by advanced analysis" as crucial elements for efficiency gains, underscoring their significance in maximizing ORC performance.

(Amit Bhowmick, 2022) Recent developments in combined cooling and power cycles have demonstrated a great deal of promise for improving processes for recovering waste heat. To increase thermodynamic and financial efficiencies, the integration of a gas turbine and a heat recovery steam generator, along with a regenerative Organic Rankine Cycle (ORC) and an ejector-absorption refrigeration cycle, has been investigated. Numerous studies demonstrate that because of its irreversible operations, the combustion chamber is frequently the main source of energy destruction. Exergoeconomic study shows that exergy destruction costs in these kinds of systems might be higher than investment costs, highlighting the necessity of performance optimization of individual components. Thermodynamic comparisons between R141b, R601a, and R123, among other working fluids, show that R141b is a more effective way to increase power output in regenerative ORC systems. Moreover, multi-objective optimizations have been carried out to strike a balance between product costs and exergy efficiency, producing workable solutions that steer clear of problems like crystallization in ejector absorption systems. The significance of combining thermodynamic and economic analysis to create waste heat recovery systems that are more economical and sustainable is highlighted by this body of research.

(Xiaoxia Xia, 2023) The potential of waste heat recovery technologies—especially those that combine vapor compression refrigeration (VCR) systems with organic Rankine cycles (ORCs)—to address the world's energy and environmental concerns has drawn a lot of attention. The conversion of low-grade waste heat into useful cooling and power is made easier by the integration of ORC and VCR systems, which improves energy efficiency and lowers emissions. The thermodynamic performance of these integrated systems has been thoroughly examined in the past, with an emphasis on their energy and exergy efficiency. While advanced exergy analysis offers deeper insights into the relationships between components and the possibility for system improvement, conventional exergy analysis aids in identifying the system's overall performance and inefficiencies. Important conclusions drawn from the literature indicate that parts like compressors, turbines, and condensers have a big impact on the exergy destruction rates and, in turn, the total system efficiency. Optimizing system performance requires prioritizing improvements in these components according to their exergy destruction characteristics. By providing ideas for improving the efficiency of ORC-VCR combination systems, this research supports the wider application of these systems in sustainable energy solutions, adding to the expanding body of knowledge.

3. Methodology, Software used and Flow chart

3.1. Purpose of the Methodology

The power generation sector is under tremendous pressure to produce energy more responsibly and effectively as the world's demand for electricity rises. The goal of this research is to improve "the efficiency and economics of combined cycle power plants, which are the cutting edge of contemporary power generation. In comparison to typical power plants, combined cycle power plants incorporate both gas and steam engines to" enhance efficiency and minimize pollution.

The following are this methodology's main goals:

- **Efficiency Improvement:** Investigating and recording different approaches and technology that can increase combined cycle power plants' efficiency and lower fuel and emission usage.
- **Cost Reduction:** To find methods and inventions that allow these power plants to run and maintain their systems at a reduced cost without sacrificing performance.
- **Enhancing Sustainability:** Including eco-friendly methods and technologies that support the sustainable development objectives, like absorption refrigeration systems, organic Rankine cycles, and cogeneration.
- **Exergy study:** To identify areas of energy loss and suggest changes, a thorough exergy study of the various components inside the power plant should be conducted.
- **Case Studies and Best Practices:** To gather best practices and case studies from currently operating power plants that have effectively incorporated cutting-edge cycles and technologies.

3.2. Combined Power Plant Cycle System

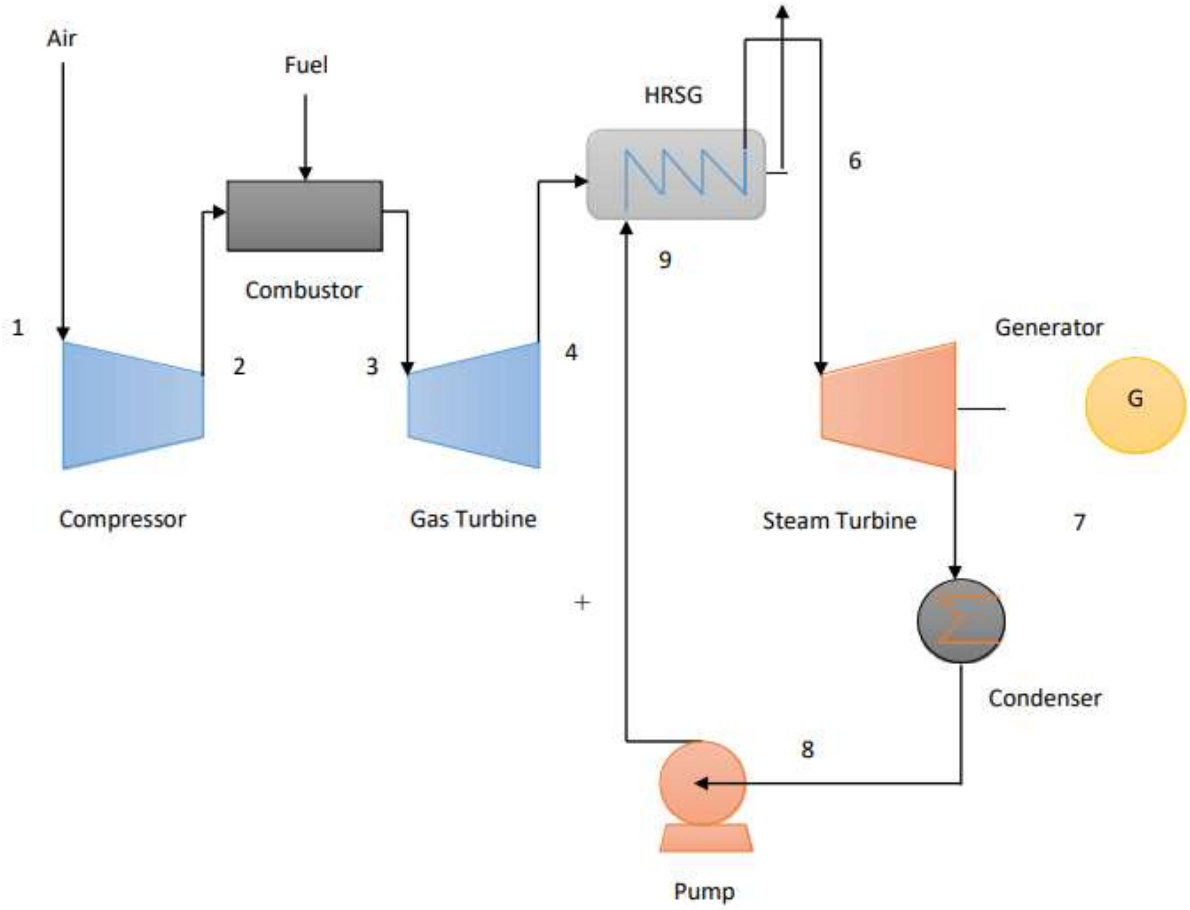

Fig .3.1. Combined cycle process

3.2.1 Detailed Explanation of Combined Cycle

3.3 Technology Overview

A combined cycle power plant combines two or more thermodynamic cycles “in order to maximize energy output and efficiency. It usually combines two cycles: one gas turbine and one steam turbine. The essential elements consist of:

- Gas turbines generate high-temperature, high-pressure gas through the burning of fuel, often natural gas. This gas powers the turbine.
- The gas turbine's exhaust heat is captured by the Heat Recovery Steam Generator (HRSG)”, which uses it to create steam.
- Steam Turbine: This device generates extra electricity by using the steam produced by the HRSG.
- Condenser: Reconsistently cools and condenses steam into water for HRSG repurposing.

3.4 Advantages of Combined Cycle Systems

Higher Efficiency

Combined cycle systems achieve higher efficiency by “utilizing waste heat from the gas turbine to generate additional electricity via the steam turbine”. Typical efficiencies range from 50% to 60%, compared to 30% to 40% for conventional single-cycle power plants.

Cost Savings The higher efficiency of combined cycle systems translates to lower fuel consumption for the same amount of power generation. This reduces operational costs and extends the life of fuel resources.

Environmental Benefits By improving efficiency, combined cycle systems reduce “greenhouse gas emissions per unit of electricity generated. The reduction in fuel consumption also lessens the environmental impact associated with fuel extraction and” transportation.

4. RESULTS AND DISCUSSION

In this project by using EES software a computational model was developed to analyze the energy and exergy.

An extensive energy and exergy analysis of the integrated combined cycle power plant was carried out in this study. The results highlight the significance of incorporating low-grade energy recovery devices, such as absorption refrigeration systems and the Organic Rankine Cycle (ORC), to improve efficiency and lessen environmental” impact.

4.1 Calculation Of Exergy Loss In Different Components

TABLE NO 1 INPUT DATA FOR CALCULATING EXERGY LOSS IN DIFFERENT COMPONENTS

Initial compressor temp	290 - 318 KELVIN(K)
Critical pressure ratio	3.5 - 11
Initial steam turbine pressure	39.9 Bar
Pressure of Condenser	0.455 - 8.45
Temperature of feed water	165K
In HRSG the pressure drop is	0.04 bar
Rate of Stream flow	27.50 kgs^{-1}
Massic heat capacity for the air	1.44
Massic heat capacity for the gas	1.333
Pressure ratio for the compressor	7.9
In the combustion chamber the pressure drop is	0.029

In Table 4.1, the initial conditions for the air entering to combustion turbine thermal power plant compressor are set at 10^5 Pascal and 300 K, with massic heat capacity (specific heat ratio) of 1.41. The air undergoes compression to a ratio of 7.9 in compressor. After compression, it expands in the combustion turbine. The initial steam turbine pressure is maintained at approximately $39.9*10^5$ Pascal. At this stage, the air is again expand further via the Parson turbine(Steam turbine), leading to a condenser pressure ranging from 0.45 to 9.45 bar. Additionally, there is a pressure drop of 0.04 bar in the heat recovery steam generator (HRSG) associated with the steam feeding into the steam turbine.

RESULT:

4.2 Entropy Generation Of Different Parts

Table2 and Figure 2 illustrate the exergy destruction occurring in different components of the combined cycle system.

TABLE NO 2 ENTROPY GENERATION OF DIFFERENT PARTS

PARTS	**Entropy generation (KW)**
Combustor	88687
Compressor	7314
HRSG	7850
Combustor Gas turbine	5682
Exhaust gases	17692
Steam turbine	6371

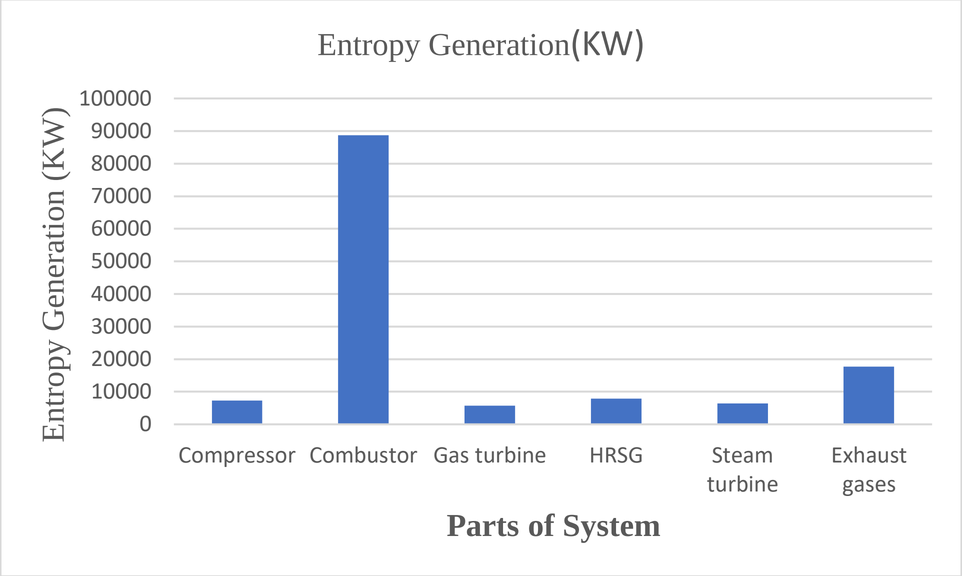

Fig.2. ENTROPY GENERATION OF DIFFERENT PARTS

In this study energy-exergy analysis is performed for the combustion chamber (88687 kilowatt). The main objectives of the exhaust gas due to destruction (17692 Kilowatt), the total exergy destruction to the environment mainly occurs in the gas turbine is 5682 Kilowatt. The total exergy destruction followed by HRSG (11.3%), steam turbine condenser (2.54%).

In the combustion chamber the value of entropy generation i.e. exergy destruction is 86106 kilowatt at the temp 318 Kelwin and the optimum value 88685 kilowatt at the temp 300 kelvin. After that it is seen decrease in available energy losses 88685 kilowatt at the temp of 300 kelvin. In the present study it is observed that the falls of available energy in plant with in increase in environment temp.

5. CONCLUSION

5.1 Conclusion

An extensive energy and exergy analysis of the integrated combined cycle power plant was carried out in this study. The results highlight the significance of incorporating low-grade energy recovery devices, such as absorption refrigeration systems and the Organic Rankine Cycle (ORC), to improve efficiency and lessen environmental" impact.

5.1.1 Greater Efficiency and Environmental Benefits:

- Comparing the integrated CCPP to conventional combined cycle power plants, efficiency gains are substantial. Energy from exhaust gases can now be recovered with the installation of the ORC, saving otherwise squandered energy. The plant's total efficiency is raised by using this energy to produce more power.
- There are significant environmental advantages as well. The integrated CCPP lowers the quantity of fuel required to produce the same amount of power by using waste heat, which lowers emissions of other pollutants and greenhouse gases. Because of this, the integrated CCPP is a greener choice than traditional power plants.

5.1.2 Exergy Analysis Insights:

- An in-depth grasp of the location and mechanism of energy losses within the power plant is possible through the use of energy analysis. It was discovered in this investigation that the combustion chamber and boiler account for the majority of energy destruction. This is because these processes entail high pressures and temperatures, which cause substantial irreversibilities.
- Reducing the compressor's inlet temperature results in higher thermal and exergy efficiency, according to the exergy analysis. This is so that there is less energy destruction in the system as a result of the compressor having to work harder at lower intake temperatures.

5.1.3 Impact of Compressor Inlet Temperature:

- A thorough investigation was conducted on the connection between plant efficiency and compressor inlet temperature. It was discovered that the plant's total efficiency rises with a drop in the input temperature. This is because lower temperatures cause less energy to be destroyed in the compressor and other plant components.
- The study also discovered that particular fuel usage decreases with lower intake temperatures. This increases the plant's overall efficiency because less fuel is needed to produce the same quantity of power.

5.1.4 Cycle Efficiency Challenges:

- Even with the increases in productivity, there are still issues that must be resolved. High exhaust losses, which happen when hot gases are released from the plant before being completely utilized, are one of the key problems. This lowers the plant's overall efficiency and results in a large energy loss.
- The compressor's heavy workload presents another difficulty. This is because the procedure involves high pressures, which need a lot of energy to sustain. Further increases in plant efficiency would result from the compressor's workload being reduced.

5.1.5 Exergy Destruction and Pressure Ratio:

- The study investigated the connection between energy destruction and pressure ratio. It was discovered that the temperature at the compressor exhaust rises with increasing pressure ratios. Because of the improved combustion caused by the greater temperature, this lowers the energy destruction within the combustor.
- Nevertheless, raising the pressure ratio also makes the compressor work harder, which can partially offset the efficiency advantages. To enhance plant efficiency overall, it is crucial to strike the ideal balance between the pressure ratio and energy destruction.

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