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# An Energy Analysis of Rayalaseema Thermal (Coal Based) Power Plant

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Abstract— **Non-Renewable Energy resources dwindling and Renewable Energy technologies still in their infant stage, there is an ever increasing need for economic use of the left fossil fuel resources. Thermal energy being the life blood of world, it is essential that thermal power plants are analyzed for their energy economy. Energy analysis based on the First Law of Thermodynamics had been found insufficient and hence the Exergy analysis based on the Second Law of Thermodynamics came into picture. Keeping this in view and with the observation that Second Law of Thermodynamics and Exergy are two of the most neglected and hence less understood concepts among students, a project on Exergy analysis was undertaken. Rayalaseema Thermal Power Project located in Kadapa, Andhra Pradesh was the subject of Exergy analysis. The capacity of the plant is 5×210 MW. As a part of analysis, the power plant was simplified into sub-systems and the locations of exergy losses were traced. Irreversibilities at each sub-system were studied and quantities of exergy losses were calculated at each location. Ways were also suggested to address these losses. The Mass, Energy and Exergy balances were the core of mathematical modeling and calculations. First Law (Energy) efficiency and Second Law (Exergy) efficiency were calculated for the plant and a significant difference was found between them. Various efficiency enhancers like Economizer, Super-heater were also analyzed for their exergy losses. The results were tabulated and graphs were plotted to show the mathematical work and correlation between various parameters in a comprehensive way. The project was an exhaustive one and the results showed that there was a scope of improving the overall efficiency. Finally it's concluded that a total review of the Plant in terms of Exergy would be of great commercial interest to the Thermal Power Project.**

Keywords— **Exergy, Efficiency, 1st Law Efficiency, 2nd Law Efficiency, Thermal Power Plant, Energy, Coal Based, Thermo Dynamics**

## I. Introduction

The name thermodynamics comes from the Greek words therme (heat) and dynamics (power), which is most expressive of the conversion from heat into power. Now a days same name is broadly interpreted to include all aspects of energy and energy transformations, including power generation, refrigeration, and relationships among the properties of matter. The First Law deals with the amounts of energy of various forms transferred between the system and its surroundings and with the changes in the energy stored in the system. It treats work and heat interactions as equivalent forms of energy in transit and offers no indication about the possibility of a spontaneous process proceeding in a certain direction. The first law places no restriction on the direction of a process, but satisfying the first law does not ensure that the process can actually occur. This inadequacy of the first law to identify whether a process can take place is remedied by introducing another general principle, the second law of Thermodynamics. The exergy method of analysis is based on the Second law of thermodynamics and the concept of irreversible production of entropy. The fundamentals of the exergy method were laid down by Carnot in 1824 and Clausius in 1865. The energy-related engineering systems are designed and their performance is evaluated primarily by using the energy balance deduced from the First law of thermodynamics. Engineers and scientists have been traditionally applying the First law of thermodynamics to calculate the enthalpy balances for more than a century to quantify the loss of efficiency in a process due to the loss of energy. The exergy concept has gained considerable interest in the thermodynamic analysis of thermal processes and plant systems since it has been seen that the First law analysis has been insufficient from an energy performance stand point. However it can specify where the process can be improved and therefore, it will signify what areas should be given consideration. The simple energy balance will not sometimes suffice to find out the system defect. In such circumstances the exergy analysis is well thought-out to be significant to locate the systems imperfections. Recently, we had new technologies for high temperature air combustion and ultra-high temperature combined cycle. In this case, it is necessary to study the exergy analysis on combustion and thermodynamic processes, because ordinary energy analysis does not have any evaluation supported at its temperature level. If we introduce the exergy analysis against energy analysis, which is supported by this temperature level, it is clear that the high temperature energy has a greater evaluation compared with low temperature one. In this particular field of engineering, it is difficult to use the ambient temperature energy of air and water, which are widely available. When we discuss power generation, high temperature energy of 1500°C and above in combined cycle has higher conversion efficiency than that of 500-600°C in steam cycle. In a thermodynamic cycle, it is necessary to consider the combustion, heat transfer and energy conversion processes, which include many kinds of effective and invalid items. So, when considering the above mentioned processes, the exergy analysis must be introduced to analyze power generation and heat pump cycles as against energy analysis. Recently a large number of studies based on exergy analysis have been carried out by many researchers all over the world in various system applications.[1] The work transfer is equivalent to maximum work, which can be obtained from that form of energy. The availability ($Ex^Q$) of heat transfer Q from the control surface at temperature T is determined from maximum rate of conversion of thermal energy to work $W_{max}$. The $W_{max}$ is given by

$$W_{max} = Ex^Q = Q\left(\frac{1 - T_a}{T}\right) \quad (1)$$

Exergy of steady flow stream of matter is sum of kinetic, potential and physical exergy $Ex^{ph}$. The kinetic and potential energy are again equivalent to exergy. The physical specific exergy Ψ depends on initial state of matter and environmental state. Energy analysis is based on the first law of thermodynamics, which is related to the conservation of energy. Second law analysis is a method that uses the conservation of mass and conservation of energy principles together with the entropy for the analysis, design and improvement of energy systems. Second law analysis is a useful method; to complement not to replace energy analysis. The first law of thermodynamics or energy balance for steady flow process of an open system is given by

$$\sum Q'_k - \dot{W}m(E_1 - \dot{E}_2) = 0 \quad (2)$$

Where E1 and E2 are respectively the energy associated with mass entering and leaving the system, $Q_k$ is heat transfer to system from source at $T_k$, and W is network developed by the system. The Second law balance for steady flow process of an open system is given by

$$\sum Ex_{Q'_k} - E\dot{x}_w + \dot{m}(_1 - _2) - IR = 0 \quad (3)$$

Where $_1$and$_2$ are available energy associated with mass inflow and outflow are respectively, $Ex_{Q'_k}$ is available energy associated with heat transfer, $E\dot{x}_w$ is available energy associated with work transfer and IR is irreversibility of process. The irreversibility may be due to heat transfer through finite temperature difference, mixing of fluids and mechanical friction. Second law analysis is an effective means, to pinpoint losses due to irreversibility in a real situation. The energy or first law efficiency$\eta_I$ of a system or system component is defined as the ratio of energy output to the energy input of system or system component,

$$\text{i.e.}\ \eta_I = \frac{\text{Desired output energy}}{\text{Input energy supplied}} \quad (4)$$

The second law efficiency is defined as

$$\eta_{II} = \frac{\text{Desired output}}{\text{Maximum possible output}} \quad (5)$$

Bejan [2] drawn outlines the fundamentals of the methods of exergy analysis and entropy generation minimization (or thermodynamic optimization-the minimization of exergy destruction). The paper begins with a review of the concept of irreversibility, entropy generation, or exergy destruction. Examples illustrate the accounting for exergy flows and accumulation in closed systems, open systems, heat transfer processes, and power and refrigeration plants. George and Park [3] discusses how to estimate the avoidable and unavoidable exergy destruction and investment costs associated with compressors, turbines, heat exchangers and combustion chambers. This general procedure, although based on many subjective decisions, facilitates and improves applications of exergoeconomics. Kotas [4] explained in this work the concept of exergy used to define criteria of performance of thermal plant. Ganapathy et al. [5] studied with an exergy analysis performed on an operating 50 MWe unit of lignite fired steam power plant at Thermal Power Station-I, Neyveli Lignite Corporation Limited, Neyveli, Tamil Nadu, India. The distribution of the exergy losses in several plant components during the real time plant running conditions has been assessed to locate the process irreversibility. The comparison between the energy losses and the exergy losses of the individual components of the plant shows that the maximum energy losses of 39% occur in the condenser, whereas the maximum exergy losses of 42.73% occur in the combustor. Kamate and Gangavati [6] studied exergy analysis of a heat-matched bagasse based cogeneration plant of a typical 2500 tcd sugar factory, using backpressure and extraction condensing steam turbine is presented. In the analysis, exergy methods in addition to the more conventional energy analyses are employed to evaluate overall and component efficiencies and to identify and assess the thermodynamic losses. Boiler is the least efficient component and turbine is the most efficient component of the plant. The results show that, at optimal steam inlet conditions of 61 bars and 475°C, the backpressure steam turbine cogeneration plant perform with energy and exergy efficiency of 0.863 and 0.307 and condensing steam turbine plant perform with energy and exergy efficiency of 0.682 and 0.260. Datta et al. [7] was presented work on exergy analysis of a coal-based thermal power plant is done using the design data from a 210 MW thermal power plant under operation in India. The exergy efficiency is calculated using the operating data from the plant at different conditions, viz. at different loads, different condenser pressures, with and without regenerative heaters and with different settings of the turbine governing. The load variation is studied with the data at 100, 75, 60 and 40% of full load. Effects of two different condenser pressures, i.e. 76 and 89 mmHg (abs.), are studied. It is observed that the major source of irreversibility in the power cycle is the boiler, which contributes to exergy destruction of the order of 60%. Part load operation increases the irreversibility in the cycle and the effect is more pronounced with the reduction of the load. Increase in the condenser back pressure decreases the exergy efficiency. Successive withdrawal of the high pressure heaters shows a gradual increment in the exergy efficiency for the control volume excluding the boiler. Aljundi [8] was presented in this study, the energy and exergy analysis of Al-Hussein power plant in Jordan is presented. The primary objectives of this paper are to analyze the system components separately and to identify and quantify the sites having largest energy and exergy losses. In addition, the effect of varying the reference environment state on this analysis will also be presented. Energy losses mainly occurred in the condenser where 134 MW is lost to the environment while only 13 MW was lost from the boiler system. The percentage ratio of the exergy destruction to the total exergy destruction was found to be maximum in the boiler system (77%) followed by the turbine (13%), and then the forced draft fan condenser (9%). In addition, the calculated thermal efficiency based on the lower heating value of fuel was 26% while the exergy efficiency of the power cycle was 25%. For a moderate change in the reference environment state temperature, no drastic change was noticed in the performance of major components. Rosen [9] reported results were of energy- and exergy-based comparisons of coal-fired and nuclear electrical generating stations. A version of a process-simulation computer code, previously enhanced by the author for exergy analysis, is used. Overall energy and exergy efficiencies, respectively, are 37% and 36% for the coal-fired process, and 30% and 30% for the nuclear process. The losses in both plants exhibit many common characteristics. Energy losses associated with emissions (mainly with spent cooling water) account for all of the energy losses, while emission-related exergy losses account for approximately 10% of the exergy losses. The remaining exergy losses are associated with internal consumptions. Dincer and Rosen [10] present effects on the results of energy and exergy analyses of variations in dead-state properties, and involves two main tasks: 1) examination of the sensitivities of energy and exergy values to the choice of the dead-state proper-ties and 2) analysis of the sensitivities of the results of energy and exergy analyses of complex systems to the choice of dead-state properties. A case study of a coal- fired electrical generating station is considered to illustrate the actual influences. The results indicate that the sensitivities of energy and exergy values and the results of energy and exergy analyses to reasonable variations in dead-state properties are sufficiently small. Erdem et al. [11] analyze comparatively the performance of nine thermal power plants under control governmental bodies in Turkey, from energetic and Exergetic viewpoint. The considered power plants are mostly conventional reheat steam power plant fed by low quality coal. Firstly, thermodynamic models of the plants are developed based on first and second law of thermodynamics. Secondly, some energetic simulation results of the developed models are compared with the design values of the power plants in order to demonstrate the reliability. Thirdly, design point performance analyses based on energetic and Exergetic performance criteria such as thermal efficiency, exergy efficiency, exergy loss, Exergetic performance coefficient are performed for all considered plants in order to make comprehensive evaluations. Yilmaz et al. [12] presented in his paper, second-law based performance evaluation criteria to evaluate the performance of heat exchangers. First, the need for the systematic design of heat exchangers using a second law-based procedure is recalled and discussed. Then, a classification of second-law based performance criteria is presented: 1) criteria that use entropy as evaluation parameter, and 2) criteria that use exergy as evaluation parameter. Both classes are collectively presented and reviewed, and their respective characteristics and constraints are given. Chen et al. [13] present performance analysis and optimization of an open-cycle regenerator gas-turbine power plant. The analytical formulae about the relation between power output and cycle overall pressure-ratio are derived taking into account the eight pressure drop losses in the intake, compression, regeneration, combustion, expansion and discharge processes and flow process in the piping, the heat-transfer loss to the ambient environment, the irreversible compression and expansion losses in the compressor and the turbine, and the irreversible combustion loss in the combustion chamber. The power output is optimized by adjusting the mass-flow rate and the distribution of pressure losses along the flow path. Reddy and Mohamed [14] present work, exergy analysis of a natural gas fired combined cycle power generation unit is performed to investigate the effect of gas turbine inlet temperature and pressure ratio on Exergetic efficiency for the plant and exergy destruction/losses for the components. Koroneos et al. [15] studied the exergy analysis of solar energy, wind power and geothermal energy. That is, the actual use of energy from the existing available energy is discussed. In addition, renewable energy sources are compared with the non-renewable energy sources on the basis of efficiency. Khaliq [16] was proposed conceptual trigeneration system based on the conventional gas turbine cycle for the high temperature heat addition while adopting the heat recovery steam generator for process heat and vapor absorption refrigeration for the cold production. Combined first and second law approach is applied and computational analysis is performed to investigate the effects of overall pressure ratio, turbine inlet temperature, pressure drop in combustor and heat recovery steam generator, and evaporator temperature on the exergy destruction in each component, first law efficiency, electrical to thermal energy ratio, and second law efficiency of the system. It also indicates that maximum exergy is destroyed during the combustion and steam generation process; which represents over 80% of the total exergy destruction in the overall system.Ivar et al. [17] was investigated a concept for natural-gas fired power plants with $CO_2$ capture using exergy analysis. Natural-gas was reformed in an auto-thermal reformer, and the $CO_2$ was separated before the hydrogen-rich fuel was used in a conventional combined-cycle process. A corresponding conventional combined-cycle power plant with no $CO_2$ capture was simulated for comparison. A base case with $CO_2$ capture was specified with turbine-inlet temperature of 1250˚C and an air-compressor outlet pressure of 15.6 bars. In this case, the net electric-power production was 48.9% of the lower heating value

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of the Natural-gas or 46.9% of its chemical exergy. The effect of increased turbine-inlet temperature to 1450˚C was investigated. Combining both measures, the net electric power production was in-creased to 53.3% of the natural-gas lower heating value or 51.1% of the natural-gas chemical exergy. On the other hand, both increased turbine-inlet temperature and the auto-thermal reformer product-feed heat exchange reduced the conversion of hydrocarbons to CO2. Nag and Gupta [18] was down exergy analysis , to reduce thermal irreversibility's a thermodynamic cycle was conceptualized for the bottoming part of a combined cycle by Kalina, which uses NH3- H2O mixture as the working substance. The effect of one of the key parameter, mixture concentration at turbine inlet on the cycle performance has been studied.

## II. Power Plant Exergy

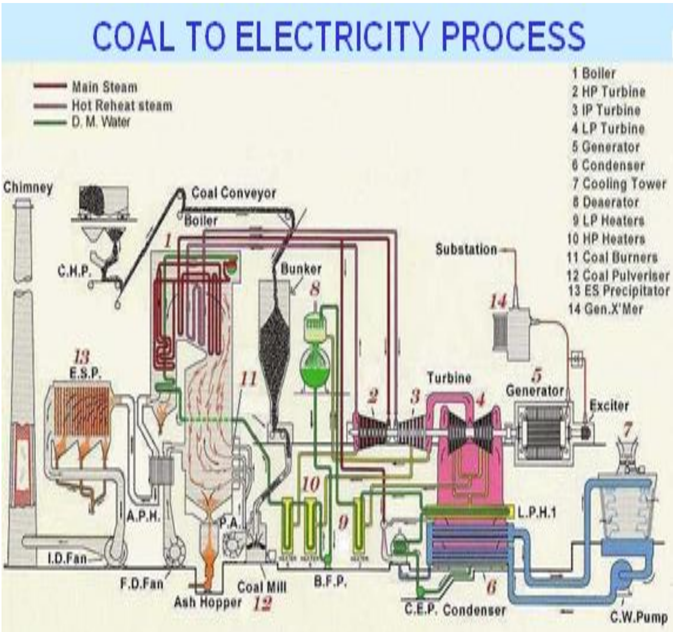


Fig.1: Working of Power Plant

Attempts to improve the performance of power plaint are a never ending subject. Until recently all of these attempts were based on the first law analysis and limited by economic and /or technical consideration recently the adequacy of the methodology was challenged by the use of the exergy concept based on the second law of thermodynamics. Many of the prominent of thermodynamics have pointed the utilization of the exergy concept to analyze steam power plaint result in accurate evaluation of the available exergy dissipation and hence more meaningful result as compared those obtained using the first law. Result show that the effects of some parameters are significantly different for the first and second law analysis.

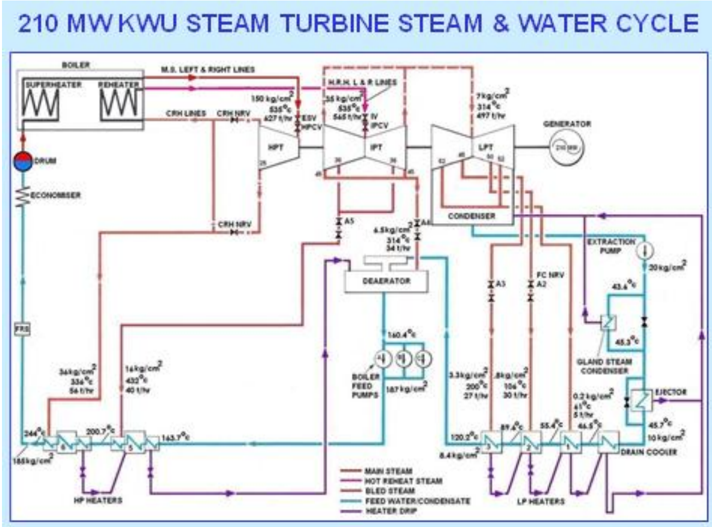


Fig. 2: Steam & Water Cycle of 210 MW Steam Turbine

A brief description of the plant operation is as follows fuel is burned in the furnace where much of the heat generated is transferred to boiler tubes which line the walls. The vapor proceeds to a super-heater. There the hot gases leaving the flame region super-heat the saturated steam produced in the boiler section. The super-heated steam proceeds to the turbine, where thermal energy is converted to mechanical energy. The steam leaving the high-pressure stage of the turbine is reheated in the furnace prior to being sent to the intermediate pressure sections and then to the low-pressure turbine proceeds to the condenser which will produce a vacuum or desired back pressure at the turbine exhaust. The liquid from the condenser is reheated in 5 regenerative feed water heaters, using steam bled from the turbine. The feed water then proceeds to the deaerator, which is an open feed water heater, to remove dissolved gases, especially oxygen and CO2, from the boiler feed water, thereby reducing corrosion levels throughout the system. The feed water then proceeds to the boiler feed pump which will increase the boiler pressure. The feed water exiting the boiler feed pump will proceed to the furnace, where it is brought to near saturation in the economizer. The gases leaving the economizer preheat the entering air and then discharged through the stack.

The objective of this study is to carry out an energy (first law) and exergy (second law) analysis of the performance of an existing 1050MW (coal-fired) electrical power plant to identify the potential for improvement. The design and actual conditions will be studied. Also, the effect of throttle steam pressure and temperature, reheat steam pressure and temperature, and effect of number of feed water heaters, both in a qualitative and quantitative sense will be discussed. The results of analyses using both the first and second law of thermodynamics for the turbine cycle of the plant operating under various conditions will be presented.

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## III. PLANT PERFORMANCE

Engineers are always curious to know how much better for performance of a plant could have been. Hence, they will thus need not just a performance, which is solely a measure of performance, but a performance criterion against which the measured value of first and second law efficiencies can be compared. The design performance parameters will be used as a performance criterion in this study. The characteristics of the employed power cycle are those of an existing 1050 MW (fuel-fired) electrical power plant. The thermodynamic state properties of the power cycle are fixed at the values shown in Tabular form. Since there is no flame temperature measurement, the actual average gas temperature is assumed to be 1600 K. The reduction in ή at low loads may be attributed to irreversibility losses in the steam generator unit and the turbine cycle unit. At the load increases, the steam generator efficiency is expected to improve and the percent heat loss of the exergy input in the steam generator is expected to decrease.

The results of the full load exergy analysis are shown in graphical form the table shows that more than 58% of the total losses occur in the (heat exchanger and furnace),24% in the turbines,5% in the condenser, 10% in the feedwater heaters,3% in the pumps.

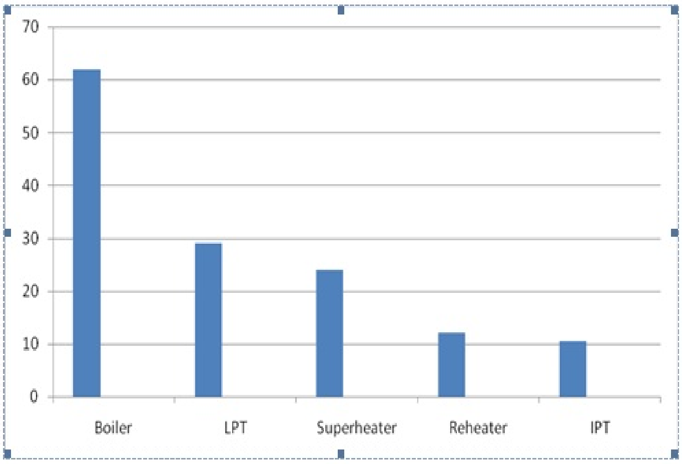


Fig 3: Exergy Destruction in Various Devices

Heat exchangers are major components in most exergy systems, and they are the source of significant losses. The high irreversibility in the heat exchanger is due to finite temperature difference between the combustion gases and the working fluid (water and steam). Heat exchangers are generally inefficient from an exergy stand point because they have been designed in the past on the basis of low first cost that dictates a minimum sized unit. To achieve the small–sized heat exchangers, the temperature difference between the fluid streams is maximized. The larger is the temperature difference in a heat exchanger, the greater will be the exergy loss during heat transfer. A combustion process usually occurs simultaneously with heat transfer. Both the chemical reaction and the heat transfer are irreversible processes. The losses in the combustion chamber are due to the increase in the entropy of the combustion gases, heat lost with the products of combustion leaving the stack and due to incomplete chemical combustion. Exergy losses in turbine are due to frictional pressure drop in the steam pipes and across the governing throttle value between the boiler and turbine.

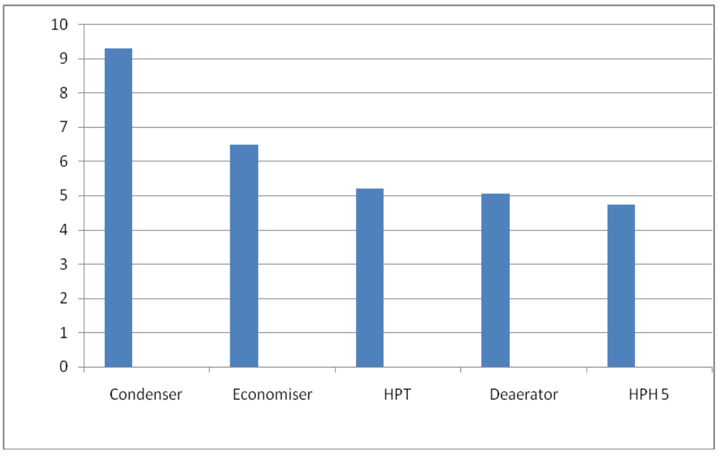


Fig 4: Exergy Destruction in Various Devices

The 5% exergy losses in the condenser are due to heat transfer between the Working fluid and cooling water which takes place at a finite temperature difference. The exergy losses in the pumps which are due to compression are usually small compared to the losses in the turbines.

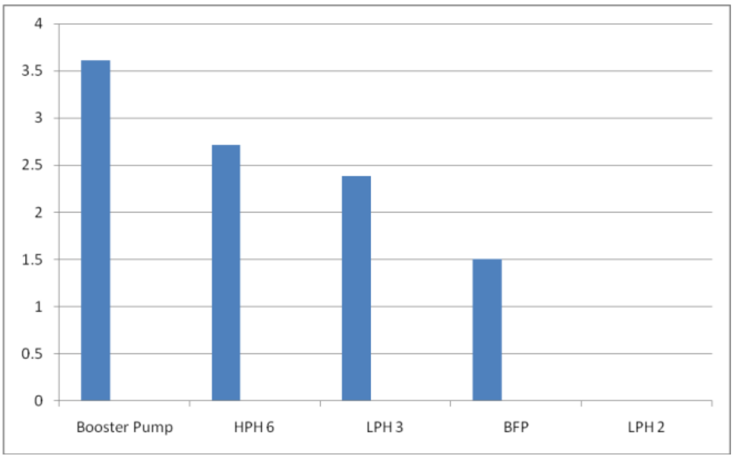


Fig 5: Exergy Destruction in Various Devices

The irreversibility of deaerator (working as heater 4) is higher than those of heater 1, 2, 3, 5 & 6 because the extraction temperature and pressure for the deaerator is done at higher values compared to those for the closed feedwater heaters. The results reveal that for this particular plant, the heat transfer process is the most inefficient operation, accounting for nearly 70% of the total exergy destruction.

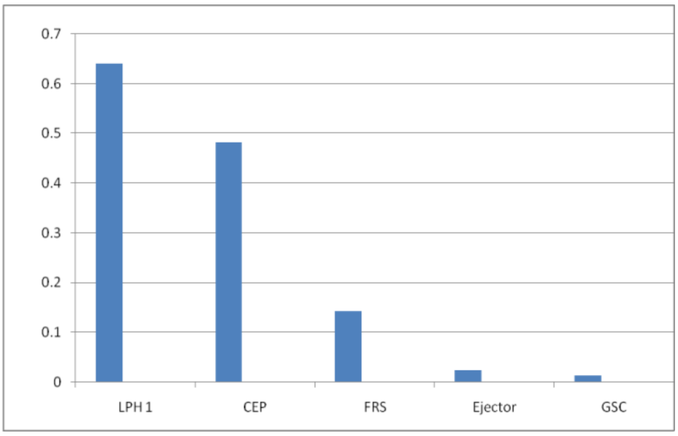


Fig 6: Exergy Destruction in Various Devices

First Law Efficiency (Energy Efficiency) of the Plant is found to be 37.97 % while, Second Law Efficiency (Exergy Efficiency) of the Plant is found to be 36.50 %. This 1.47 % difference can be attributed to the fact that the exergy of the coal is higher than the HHV of the coal.

Although the difference is just a mere 1.47 % but improving the energy efficiency by 1.47 % too can bring lots of savings in terms of operational cost, thus paving way for cheaper and cleaner Electricity.

## IV. Economics of Electric Power Production

One of the principal components of electric power cost to the consumer is the generation cost. The generation cost generally represents about 60% of the total cost of electric power to the consumer and is the main concern of power engineers responsible for power plant economics. One of the three major cost elements of generation is the fuel cost – For fossil-fueled power plants, this includes the cost of gas, petroleum or coal and interest charges on fuel reserve required at plant sites. In this section the savings in fuel cost for one year will be evaluated for 1% improvement in the overall plant efficiency. The improvements can be achieved by several alternative arrangements such as: increasing number of feedwater heaters and increasing the throttle steam temperature.

## V. Parametric Study

The results of the comparative study indicated that, there is an improvement in the plant performance. The incentive for improving performance is enormous: a 1% change in performance represents millions of Rupees in operating costs as has been reported in the previous section. Hence, this section deals with the potential for improving the efficiency. Several alternative arrangements to improve the efficiency will be considered. The results of analysis using both the first and second law of thermodynamics for the turbine cycle of the plant operating under various conditions will be presented. The physical quantities whose effects were examined are: throttle steam pressure and temperature, reheat steam pressure and temperature, effects of number of reheats and effect of number of feed water heaters. Although the throttle steam conditions have been progressively tending toward higher temperatures and pressures, they have never been formally standardized.

## VI. Conclusions

RTPP was the subject of the Exergy Analysis. The results indicated that there is a room for improvement in the plant performance. Being encouraged by these results and the fact that improvement in the performance will results in savings of millions of Rupees per year, a full exergy analysis were carried out to identify the potential for improving the performance of the plant.

The study shows that the optimum reheat pressure for a single reheat is 38 bar however, the operating reheat pressure is around 35 bar. Operating at the optimum reheat condition will improve the plant efficiency by about 0.05%. The study shows that having 2 reheaters instead of a single reheater will improve the turbine cycle efficiency by 1.1% if operated at the optimum conditions.

Increasing the degree of reheat by 50K will improve the turbine cycle efficiency by about 0.44%.

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