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Second law analysis of super critical power plant using entropy generation method

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Abstract

The increasing demand of power has made the power plants of scientific interest, but most of the power plants are designed by the energetic performance criteria based on first law of thermodynamics only. The real useful energy loss cannot be justified by the fist law of thermodynamics, because it does not differentiate between the quality and quantity of energy. Energy analysis presents only quantities results while exergy analysis presents qualitative results about actual energy consumption. In this analysis shows exergy efficiency is less at each and every point of unit equipment's. Also presents major losses of available energy at combustor, superheater, economizer and air-pre heater section. In this article also shown energy exergy efficiency, exergy destruction and energy losses comparison charts. The primary objectives of this work is to analyze the system components separately and to identify and quantify the sites having largest energy and exergy losses at different load. A numerical code is established to perform the calculations required for the thermal and exergy plant analysis considering real variation ranges of the main operating parameters such as pressure, temperature and mass flow rate. The effects of theses parameters on the system performances are investigated.

Keywords: Second Law Analysis, Super Critical Power Plant, Thermodynamic Analysis, Irreversibility optimization

1. Introduction

A power plant is defined as the assembly of equipment that generates a flow of mechanical or electrical energy. The equipment used is known as the generator. Power plants are generally classified into two types: conventional power plants and non-conventional power plants, and they are classified based on the electricity generation devices and fuel. Power plants classified regarding the electricity generation devices such as turbines are called conventional power plants. Examples of conventional sources of energy include coal, natural gas, petroleum, and water power. The device that drives electricity generation determines the kind of power plant. For instance, steam turbine plants use the dynamic pressure generated by expanding steam to run the blades of a turbine. Some other kinds of the conventional power plants are: gas turbine plants, combined cycle plants, internal combustion plants, pulverized coal-fired power plants, circulating fluidized bed power plants, pressurized fluidized bed power plants, integrated gasification cycle power plants, hydro-electric power plants, nuclear power plants, diesel power plants, steam turbines, and steam engines. Among the above different kinds of power plants, steam turbines, steam engines, diesel power plants, and nuclear power plants are categorized as the thermal power plants because they convert heat into the electric energy. Power Plants that are classified based on fuel type are called non-conventional power plants. Some of the fuels used are biomass, solar, biogas, wind, tidal, and geothermal. Some examples of the power plants are thermo-electric generator, fuel cell power plants, photovoltaic solar cell power systems, fusion reactors, geothermal energy, plants, wind energy power systems, tidal wave plants, and biogas and biomass energy power system. In India electricity sector had an installed capacity of 303 GW as of 30 Jun2016. Renewable plants constituted 28% of total installed capacity and Non-

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Renewable Power Plants constituted the remaining 72%. The total electricity generated by utilities is 1,106 TWh (1,106,000 GWh) and 166 TWh by captive power plants till date. Gross electricity generation includes auxiliary power consumption of power generation plants. India became the world's third largest producer of electricity in the year 2013 with 4.8% global share in electricity generation surpassing Japan and Russia.

This paper mainly deals with followings

1. Detailed energy and exergy analysis of different component of super critical power plant
2. Parametric Studies of different parameters with respect to different factors like comparison of first law and second law efficiency with temperature and pressure.

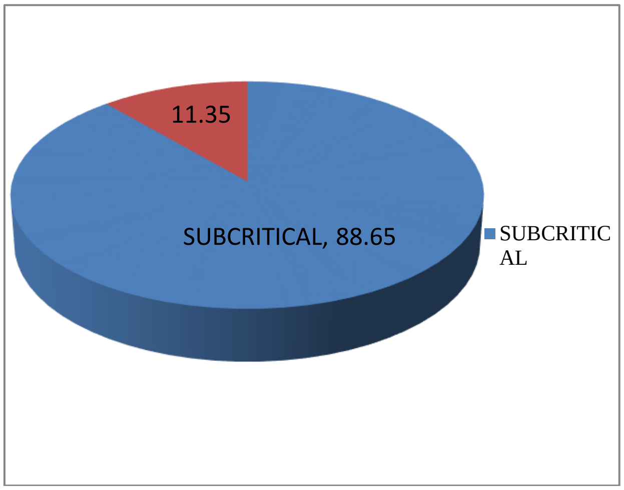

Figure 1: Percentage of super critical power plant

3. Variation of thermal performances with the changes in different component at different values of temperature and pressure.

2. Literature Review

The electricity sector in India supplies the world’s 6th largest energy consumer, accounting for 3.4% of global energy consumption by more than 17% of the global population. Due to the fast paced growth of Indian economy there has been an average increase of 3.6% in the energy demand per annum over the last 30 years.

Mukesh gupta et.al [1] analyzed the exergy of a power plant as the way to approach the analysis of a power plant. The study points out that the boiler, combustor and turbine are the critical components where maximum exergy losses occur. The first law analysis shows major energy loss has been found to occur in condenser. The second law (Exergy) analysis shows that combustion chamber in both steam and gas turbine thermal power plants are main source of Irreversibility. The Irreversibility in condenser is insignificant, because in the condenser the low quality energy is lost. An Exergy method of optimization gives logical solution improving the power production opportunities in thermal power plants. Satyanarayana et.al [2] performed energy and exergy analyzes of the cycle in the pressure range between 200bar to 425 bar and temperature range are 5000C-8000C. First law analysis and second law analysis has carried out throw with and withot reheat. The irreversibility and fractional exergy loss are determined for the cycle with and without reheat. It is found that the cycle efficiency is high in reheat than the nonreheat supercritical cycle. It is also conclude that exergy efficiency is high in reheat than non-reheat supercritical cycle. It is found that nearly 20-25% irreversibility is reduced by using single reheat in the boiler, where as it is 12-15% in the turbine than the without reheating. Fractional exergy losses of all the components in the cycle is determined and compared with and without supercritical cycle..Pandey et.al.[3] concluded that the energy efficiency of the cycle increases as a result of using regeneration, open FWH and closed FWH. From the exergy analysis it is found that the exergy losses due to irreversibility were maximum in the boiler than in the turbine followed by the condenser. Further it was seen that the fractional irreversibility in the boiler increases with turbine inlet temperature whereas it decrease with increase in boiler pressure. In the present work a simple reheat-regenerative rankine cycle was considered for calculation of energy efficiency, exergy efficiency and the irreversible losses. S C kaushik et.al.[4] carried out the energetic and exergetic analysis on a 660 MWe coal fired supercritical thermal power plant at 100%, 80% and 60% of normal continuous rating (NCR) conditions under constant pressure as well as pure sliding pressure operation and to highlight the benefits of the latter over the former. The energetic input, energetic output, exergetic input, exergetic output, energetic and exergetic efficiencies of various components of the supercritical thermal power plant are estimated at 660 MWe, 528 MWe and 396 MWe load under both constant pressure as well as pure sliding pressure operation. Also the energy losses and exergy destruction in various components of a power plant i.e. Boiler, high pressure turbine (HPT), intermediate pressure turbine (IPT) , low pressure turbine (LPT), condenser, gland steam coolers, condensate extraction pumps, low pressure heaters (LPH), drip pumps (DP), deaerator (D), boiler feed pump (BFP) and high pressure heaters (HPH) have been calculated. The results have shown that the boiler has the maximum rate of exergy destruction than any other component in the power plant. After the boiler, turbine has the maximum rate of exergy destruction than any other component of the power plant. The study reveals that there is a significant reduction in the rate of exergy destruction at part load conditions for the turbine in case of sliding pressure operation in comparison to constant pressure operation. S

C kaushik et.al [5] carried out the energetic and exergetic analysis of natural gas fired combined cycle power plant, Linear Fresnel Reflecting Solar Concentrator and also solar aided natural gas fired combined cycle power plant. The exergetic analysis shows that combustion chamber subsystem followed by heat recovery steam generator (HRSG) is main source of exergy loss in a natural gas fired combined cycle power plant. The exergetic power loss in the condenser is less. In the analysis linear Fresnel reflecting solar concentrator (LFRSC) by increasing focal distance and decreasing width linear Fresnel reflector, total reflector area come close to actual reflector area. By the increasing of normal incidence beam solar radiation (Ib) both energetic and exergetic efficiencies increases. Increasing inlet temperature and decreasing the mass flow rate of thermic fluid exergetic efficiency is increased. Sandhya hasti et.al [6] performed 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 Excel .The model was based on the concepts of coal combustion, energy balances, enthalpy balances, entropy changes and heat transfer of the steam power cycle. After development, the validated model was used to simulate the hypothetical power plant combusting lignite coal with the net output of 422 MW. The exergy loss indicates that the highest concentration of losses appears to be the furnace followed by the turbine. M.K. Gupta et.al , [7] carried out energy and exergy analysis for the different components of a proposed conceptual direct steam generation (DSG) solar–thermal power plant (STPP). It has been found that the maximum energy loss is in the condenser followed by solar collector field.The maximum exergy loss is in the solar collector field while in other plant components it is small. The possibilities to further improve the plant efficiency are identified and exploited. For minimum exergy loss in receiver the inlet temperature of water to the receiver, which is governed by the number of feed water heaters (FWHs), bleed pressure and mass fraction of bleed steam, must be optimum. V. Siva Reddy et.al [8] carried out energetic and exergetic analysis for natural gas fired combined cycle power plant, Linear Fresnel Reflecting Solar Concentrator and also solar aided natural gas fired combined cycle power plant. The exergetic analysis shows that combustion chamber subsystem followed by heat recovery steam generator (HRSG) is main source of exergy loss in a natural gas fired combined cycle power plant. It is observed that the utilization of solar energy for feed water heating and low pressure steam generation is more effective based on exergetic analysis rather than energetic analysis. Ligang Wang et.al [9] performed exergy analysis on supercritical coal-fired power plant. The results show that the ratio of exogenous exergy destruction differs quite a lot from component to component. In general, almost 90% of the total exergy destruction within turbines comes from their endogenous parts, while that of feed water preheaters contributes more or less 70% to their total exergy destruction. Moreover, the boiler subsystem is proven to have a large amount of exergy destruction caused by the irreversibilities within the remaining components of the overall system. It is also found that the boiler subsystem still has the largest avoidable exergy destruction. S.K. Soma et.al [10] studies thermodynamic irreversibility and exergy analysis in the processes of combustion of gaseous, liquid and solid fuels. The need for such investigations in the context of combustion processes in practice is first stressed upon and then the various approaches of exergy analysis and the results arrived at by different research workers in the field have been discussed. It has been recognized that, in almost all situations, the major source of irreversibility's is the internal thermal energy exchange associated with high temperature gradients caused by heat release in combustion reactions. The primary way of keeping the exergy destruction in a combustion process within a reasonable limit is to reduce the irreversibility in heat conduction through proper control of physical processes and chemical reactions resulting in a high value of flame temperature but lower values of temperature gradients within the system. V. Raghavan et.al. [11] has performed entropy generation during the quasi-steady combustion of spherical liquid fuel particles .The effects of free stream velocity, particle diameter, ambient temperature and gravity, on the entropy generation rate, have been discussed in detail. In the range of subcritical freestream velocity, where an envelope flame is present, the entropy generation rate presents a minimum value. At a critical velocity, where the flame transition occurs, the entropy generation rate reaches a maximum value. Flame transition significantly affects the entropy generation rate, which suffers a sharp decrease in its value after the transition. Meeta Sharma et.al. [12] has performed exergy analysis of a dual pressure (DP) heat recovery steam generator (HRSG) having steam generation at high pressure (HP) and low pressure (LP) in the range of 50–70 bar and 2–6 bar respectively in the gas/steam combined cycle power plant for varying dead states. The in-operation plant data for this study are taken from a gas/steam combined cycle power plant at Auraiya (U.P.), India. Results have been obtained for exergy loss and exergy efficiency with varying dead state temperatures for different HP and LP steam generation states in different sections of HRSG. The exergy analysis for chosen conditions/parameters helps in locating the particular sections of the HRSG having maximum exergy loss. It is found that at varying steam generation pressures the HP and LP super heater sections and at higher dead state temperatures the HP evaporator are found to act as major source of irreversibilities. Cuneyt Uysal et.al [13] carried out the exergetic and thermo economic analyses of a coal-fired power plant with 160 MW capacity where located in Turkey were performed. Specific Exergy Costing (SPECO) and Modified Productive Structure Analysis (MOPSA) methods were separately applied to the system to determine the unit exergy cost of electricity generated by the coal-fired plant. The differences of these methods were discussed. As a result, the exergy efficiency of coal-fired power plant is found to be 39.89%. The equipment having the highest improvement potential is determined as boiler. Ravinder Kumar[14] concluded that the maximum energy loss occurs in the condenser and next to it is boiler. The major exergy destruction has been found in the boiler. It was found that the cost of exergy destruction in the boiler and turbine is higher in comparison to the other components cost. In case of gas fired power plant, it was found that the combustor is the most inefficient apparatus and is the major destructor of exergy. In a combined cycle power plant the highest exergy destruction is caused by the combustion chamber using both conventional and advanced exergetic analyses. Ningning Si, et.al [15] evaluated the thermal performance of a 1000 MW double reheat ultra-supercritical power plant. An exergy analysis was performed to direct the energy loss distribution of this system. Based on the exergy balance equation, together with exergy efficiency, exergy loss coefficient, and exergy loss rate, the exergy distribution and efficiency of the unit were determined. Results show that the highest exergy loss in furnace is as high as 85%, which caused by the combustion of fuel and heat exchange of water wall. Kwang Y. Lee et.al [16] analyzed that ultra-super-critical (USC) boiler power plants are currently being developed to increase the efficiency of standard fossil fuel power plants. The modelling and control of a large-scale 1000 MW once-through type ultra-super-critical boiler power plant is investigated here. Larger more complicated power plants require more sophisticated methods to streamline the modelling process as well as more sophisticated control schemes that can be used to further enhance plant efficiency. Sairam Adibhatla et.al [17] carried out thermodynamic analysis of integrate solar aided feed water heating with a 500 MWe sub critical coal fired thermal power plant. Complete bleed steam substitution in high pressure heaters (HPH) has been attained by placing a feed water heat exchanger (FWHE) in parallel to the HPH group for solar aided feed water heating. Exergy and thermo economic analyses have been performed on both reference 500 MWe and conceptual solar aided 500 MWe thermal power plants. The exergy analysis has revealed that the solar field followed by boiler have the maximum exergy destruction ratios of 78.90% and 56.52% respectively. The corresponding second law efficiencies of solar field and boiler are 21.10% and 43.48% respectively. Thermo-economic analysis has been performed on both the plants by developing physical and productive structures for them. A set of linear equations have been developed and solved for finding the cost rates of different product streams. Many investigators have not carried out following.

1. Entropy generated in each component need to be calculated.
2. Factors affecting loss of exergy need to be analyzed
3. And actions to be defined to minimize the exergy loss.
4. Difference between first law and second law efficiency.

   The present investigations mainly deals with mentioned above research gap identified.

3. Results and Discussions

After the analysis of different cycles on which the super critical thermal power plant work with respect to energy, exergy. The exergy destruction shows a loss that can be recovered by using the suitable design of the various parts of the system and also it confirms the best possible operation of the power plant according to second law of Thermodynamics. As the exergy destruction shows a loss, which can be quantify by analysis the system in mathematically. In the present work the analysis is done in the super critical steam power plant.

From Fig2 the network output from turbine will decrease with increase in boiler pressure as the temperature at inlet of turbine is constant and as a result the area under the curve will decrease.

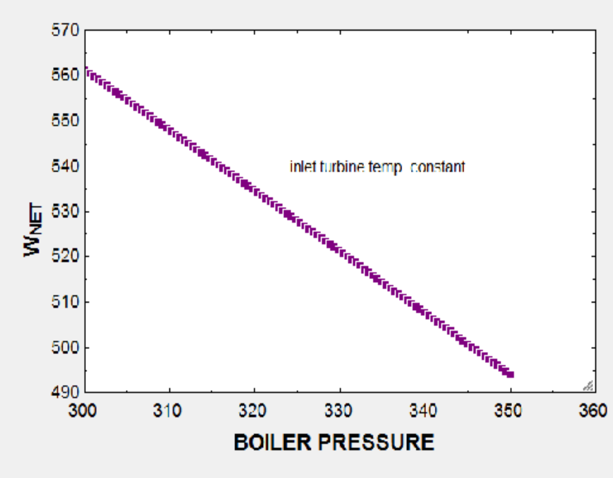

Figure 2: Variation of net-work output with boiler pressure

The first law efficiency of cycle will decrease as boiler pressure increases as net work output from turbine will decrease with increase in boiler pressure as the temperature at inlet of turbine is constant and as a result the area under the curve will decrease as shown in Fig-3 respectively. The area under the curve show the net work obtained and heat supplied is constant so efficiency of cycle will decrease.

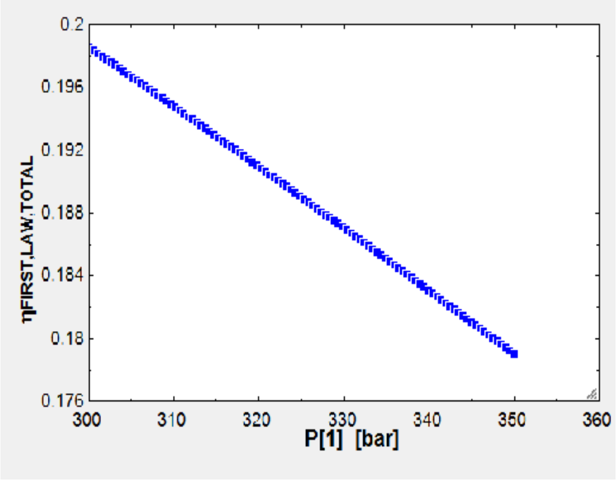

Figure 3: *Variation of first law efficiency with boiler pressure*

The variation of the boiler with T1 and P1 is shown in Fig. Exergy destruction increase with increase in T1 and P1. As exergy destruction is due to entropy generation and increase in temperature leads to more entropy generation hence more exergy destruction as shown in Fig-4

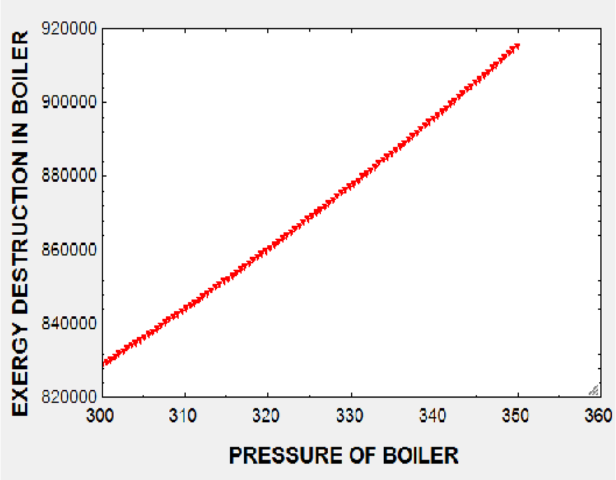

Figure 4: Variation of exergy loss in boiler with boiler pressure

The variation of the I_{cond} with T_1 and P_1 is shown in Fig. Exergy destruction increases with increase in T1 and P1. As exergy destruction is due to entropy generation and increase in temperature leads to more entropy generation hence more exergy destruction in the condenser as shown in Fig-5

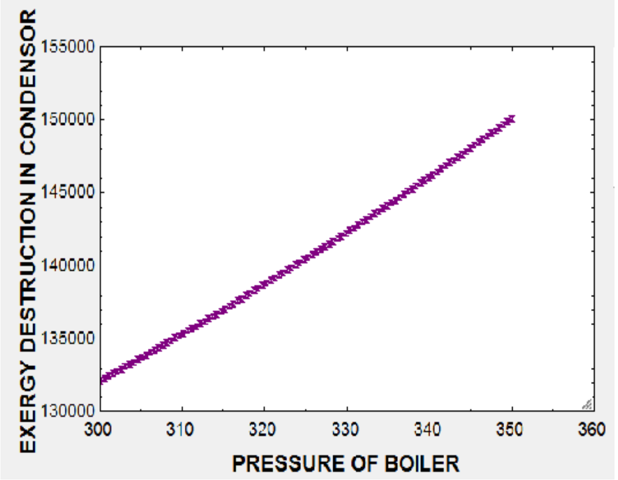

Figure 5: Variation of exergy loss in condenser with boiler pressure

As boiler pressure increases exergy loss also increases in turbine. As exergy destruction is due to entropy generation and increase in temperature leads to more entropy generation hence more exergy destruction in turbine as shown in Fig-6.

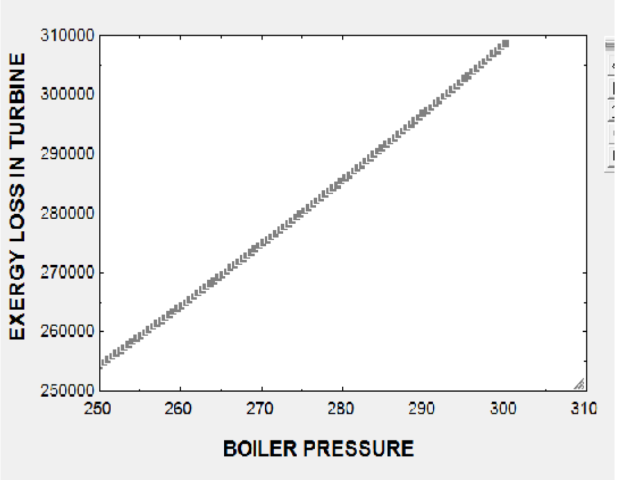

Figure 6: Exergy loss in turbine vs boiler pressure

Exergy loss in different component is calculated below. The maximum exergy loss occurs in boiler and then in turbine than in condenser but as per first law analysis maximum energy loss was in condenser but it was low energy loss. As shown in Fig-7.

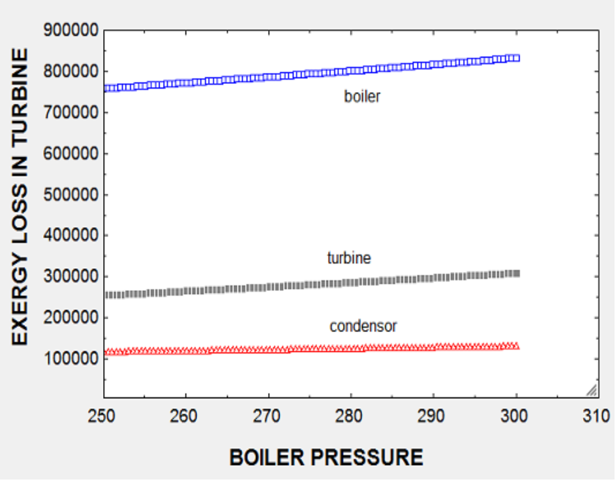

Figure 7: Variation of Exergy loss in different component

The variation of the W_t with T_1 is shown in Fig. Work output increases with increase in T1. As area under the curve increases. Hence net work output from turbine will increase as shown in Fig-8 respectively.

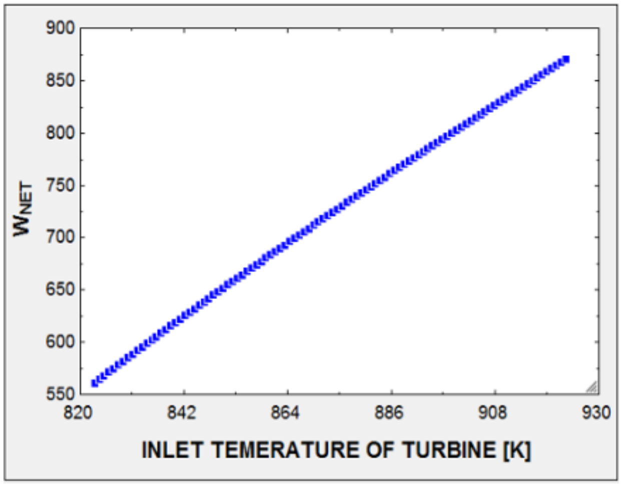

Figure 8: Variation of net work (W_net) with inlet temperature of turbine

The variation of the ηt1 with T1is shown in Fig. First law efficiency increases with increase in T1. As we have seen earlier in graph with temperature increase net work output will increase as compared to heat supplied as a result overall efficiency of cycle will increase as shown in Fig-9.

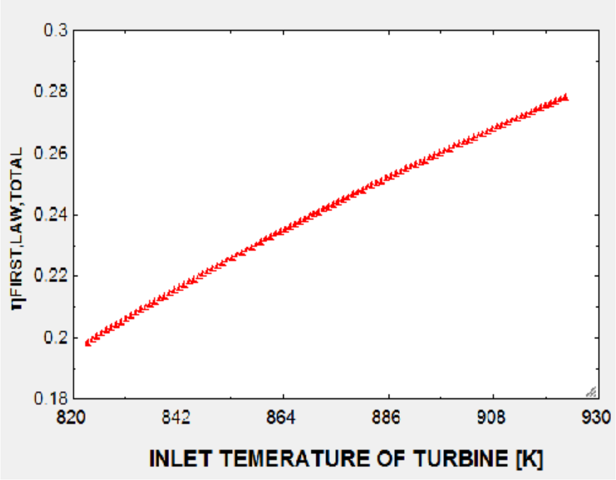

Figure 9: Variation of First law efficiency of cycle with inlet temperature of turbine

The variation of the η2t with T1 is shown in Fig. Second law efficiency decreases with increase in T1. As we increase the temperature, more entropy will be generated as a result more destruction of exergy hence efficiency will decrease as shown in Fig-10

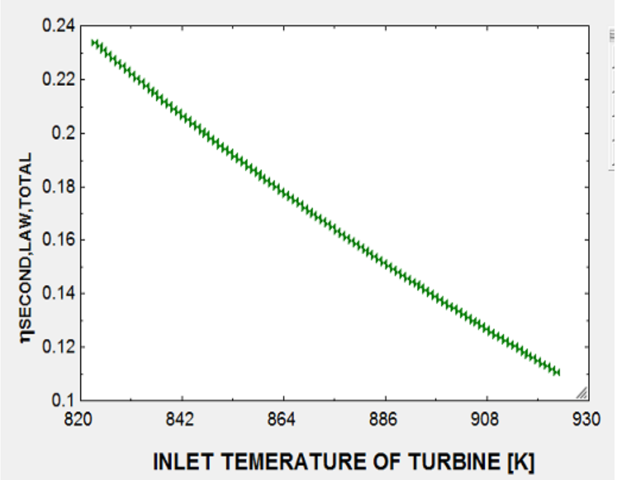

Figure. 10: Variation of second law efficiency of cycle vs inlet temperature of turbine

Fig-11 shows the Exergy destruction in boiler**.** As temperature increases more entropy will be generated as a result more exergy loss. Major exergy loss occurs in furnace part than in heat transfer part of boiler. So boiler is the main component where major exergy losses occur.

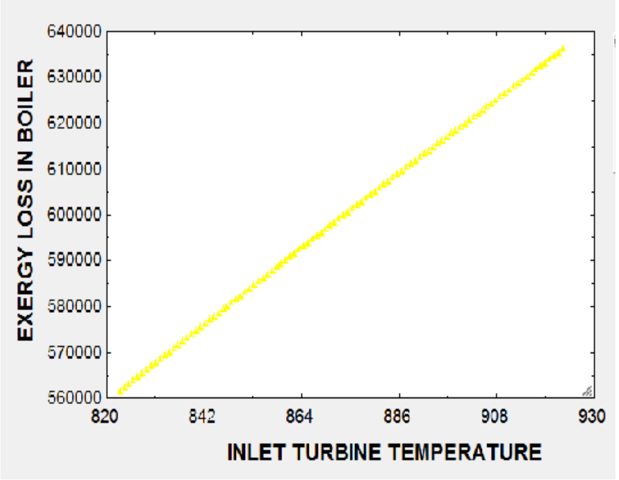

Figure 11: Variation of exergy loss in boiler with inlet temperature of turbine

The maximum exergy loss occurs in boiler and then in turbine than in condenser but as per first law analysis maximum energy loss was in condenser but it was low grade energy loss as shown in Fig-12.

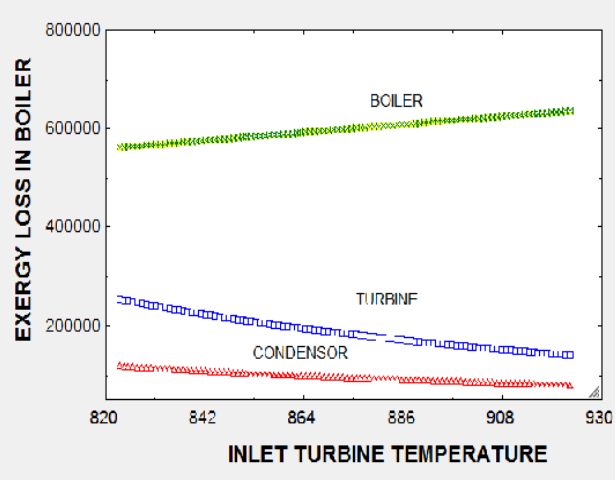

Figure 12: Variation of exergy loss in boiler vs inlet temperature of turbine

The variation of the W_t with mass flow rate is shown in Fig. Work output decrease with increase in mass flow rate. It is due to with high mass flow rate no. of losses in different component increases as a result overall performance decreases as shown in Fig-13

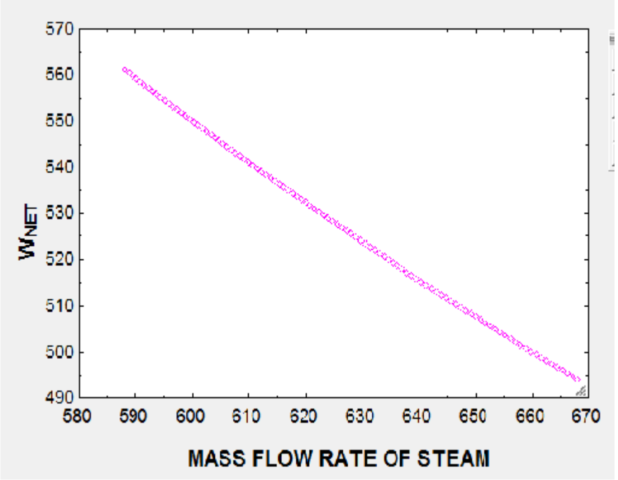

Figure 13: Variation of work output vs mass flow rate of steam

The variation of the second law efficiency in terms of exergetic efficiency (η2t) with mass flow rate is shown in Fig-14. . Second law efficiency decrease with increase in mass flow rate.

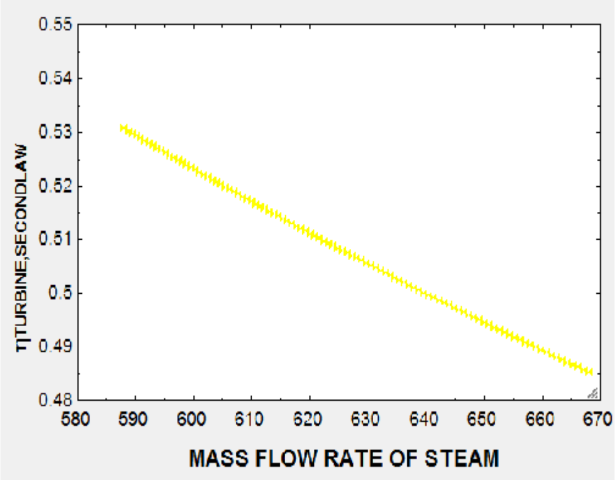

Figure 14: Variation of second law efficiency vs mass flow rate of steam

As mass flow rate increases first law efficiency decreases. It is due to with high mass flow rate no. of losses in different component increases as a result overall performance decreases. Therefore first law efficiency of cycle decreases as shown in Fig-15

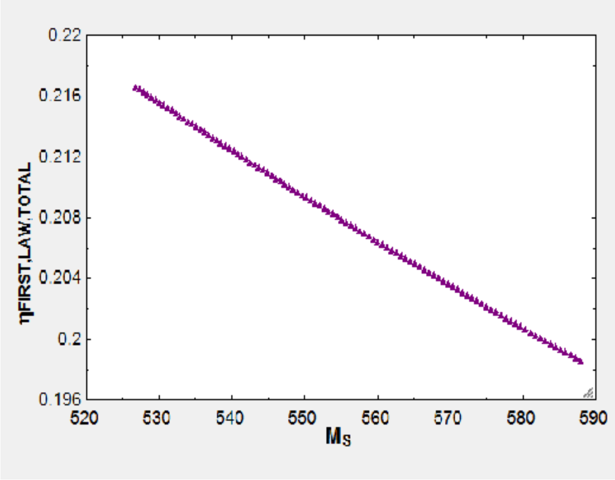

Figure 15: Variation of first law efficiency vs mass flow rate of steam

The maximum exergy loss occurs in boiler and then in turbine than in condenser but as per first law analysis maximum energy loss was in condenser but it was low grade energy loss.

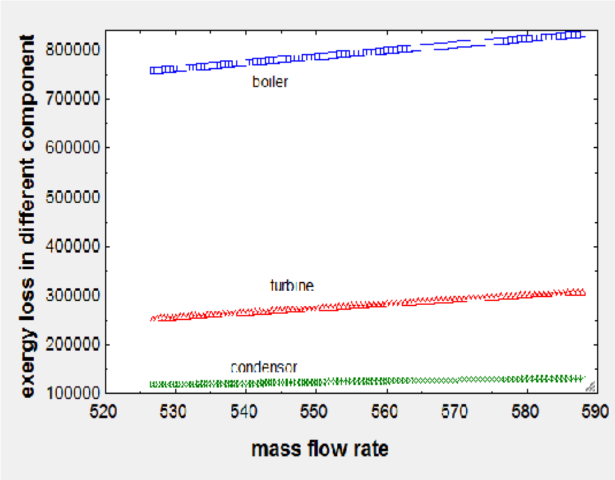

Figure 16: The variation of exergy loss in different component vs mass flow rate of steam

4. Conclusions and Recommendations

A second law of thermodynamic analysis was performed for a supercritical power plant to explore the performance of individual components. From the exergy analysis results obtained, the furnace was identified as having the highest exergy destruction. The turbines had the second highest exergy destruction rate.

Some of the conclusions regarding the exergy destruction of different components and options to reduce the exergy destruction in the furnace and turbine are given below:

1) Exergy destruction rate was greater in the combustor than the heat exchanger unit. The factors responsible for the furnace exergy losses were excess air percentage, preheated air temperature, and moisture content in the coal.

2) The exergy loss depends purely on the temperature range of the input and outlet stages of the turbine series. The exergetic efficiency increased in accordance with an increase in the reheating temperature.

3) As temperature of inlet turbine increases the exergy destruction in different component increases same happens with increase in pressure also. If exergy losses are avoided, overall efficiency can be increased.

The following are the recommendations for the future work: For the power plant to operate at a very high temperature and pressure, it is important to focus more on the plant design. An advanced material is required to design a steam turbine that can withstand high temperature that is around 700 C. The steam turbine has to be designed in such a way that it matches the furnace conditions. Future research should also focus on identifying a coating that can withstand the high temperature and pressure and protect the equipment from steam oxidation and erosion inside the turbines. Also, the material properties throughout the overall design of an ultra-supercritical power plant using coal as the fuel should be investigated.

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