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Implementing Results of Exergy Analysis in Steam Turbine Power Plants

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ABSTRACT

Energy and Exergy analysis give us important information which is helpful in improving the performance of a power plant. However, energy analysis does not emphasize on its quality while exergy analysis does. This paper briefly reviews the energy and exergy analysis carried out in various steam turbine power plants and summarizes the findings of those studies. Most studies suggest that maximum exergy destruction takes place during the combustion process and also during the heat transfer process. However, very few studies make constructive suggestions about the further course of action needed to improve the plant performance. Moreover, the suggestions made are not practically verified in most cases. Hence, this paper attempts to consolidate all the suggestions that have been made to implement the findings of the exergy analyses in steam turbine power plants. The suggestions are put together under the heads of (i) Low cost, (ii) Combustion related, (iii) Heat transfer related and (iv) Other sources of improvements. From the results, it is understood that largest scope for improvement lies in the areas of combustion and heat transfer even though the technology to improve may not be available in every aspect. More pragmatic suggestions include sliding pressure control instead of constant pressure operation at part loads.

KEYWORDS: Energy, Exergy, Analysis, Irreversibility, Power Plants, Suggestions

1 INTRODUCTION

Most of the world's energy requirements are met by both steam turbine based thermal power plants. Most utility steam turbine power plants are of 500 to 2000 MW capacities while gas turbine power plants are not used as stand alone for power production. They are mostly used as the topping cycle in a combined cycle power plant involving a gas turbine and steam turbine power plant. Unlike hydro-electric power plants, the steam and gas turbine power plants' performance is limited by the laws of thermodynamics. Due to this reason, the highest thermal efficiencies achieved are around 60% and that too under combined cycle mode with high steam and gas operating parameters.

Siva Reddy et. al. [1] have projected the power production from 2007 to 2035. They observed that the energy generated from coal increases by 2.3% every year in this period and the total energy produced by 2035 by coal is around 15 trillion kWh. The ever increasing energy demand is putting pressure on power plant designers- especially those of thermal power plants (steam and gas turbine) to increase the thermal efficiency. Hence the designers heavily rely on energy analysis which points at energy conservation measures. However, energy is a quantitative term and its usefulness is dependent on its quality. For example, an energy analysis on a steam turbine power plant indicates that more than 60% of energy is lost in the condenser. Hence a design engineer would be tempted to curb this loss. However, this energy is at a low temperature of about 50 ^{0}C and hence is of no use in an environment at around 25 ^{0}C. The usefulness of the available energy is determined by what is called as the Second Law analysis or the Exergy Analysis. The Exergy Analysis throws light on the energy losses which are worthwhile to act upon. For example, an exergy analysis of a steam turbine power plant suggests that most of the useful energy is lost in the boiler involving combustion and heat transfer and least useful energy is lost in the condenser. This is exactly opposite to what an energy analysis suggests. Therefore, an exergy analysis suggests the areas which needs to be focused upon to improve the performance of a power plant.

However, most studies on exergy analysis of power plants stop at highlighting the areas in which useful energy is lost or where the irreversibilities are maximum. Often, no constructive suggestions are made which will help the design engineer to improve the performance. This is like pointing out the problem but offering no solution. Hence this paper attempts to make practical suggestions to improve the performance of steam turbine power plants. It is to be noted that the suggestions made involve cost and hence exergy analysis needs to be carried out together with economic analysis to determine the extent of implementation and the breakeven point.

2 MASS, ENERGY AND EXERGY ANALYSIS IN A STEADY FLOW SYSTEM

Even though a steam turbine power plant operates in a closed loop (at least theoretically) on the water side, each and every component is an open system. Once, the entire system reaches a steady state, each component i.e. the boiler, turbine, condenser and pump can be treated as an open system and the flow through them can be treated as steady. Mass, energy and exergy related calculations are performed based on standard concepts of mass and energy conservation and exergy balance. The following equations and notation was adapted from Cengel and Boles [2].

2.1 MASS BALANCE IN A STEADY FLOW SYSTEM

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \tag{1}$$

2.2 ENERGY BALANCE IN A STEADY FLOW SYSTEM

$$\sum_{in} \dot{E} = \sum_{out} \dot{E} \tag{2}$$

For multiple streams:

$$\dot{Q} - \dot{W} = \sum_{out} \dot{m}\left(h + \frac{V^2}{2} + gz \right) - \sum_{in} \dot{m}\left(h + \frac{V^2}{2} + gz \right) \tag{3}$$

For single stream:

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \right] \tag{4}$$

2.3 EXERGY BALANCE IN A STEADY FLOW SYSTEM

$$\underbrace{\dot{X}_{in} - \dot{X}_{out}}_{\substack{\text{Rate of net exergy} \\ \text{transfer by heat,} \\ \text{work, and mass}}} - \dot{X}_{destroyed} = 0 \tag{5}$$

$$\dot{X}_{heat} = \left(1 - \frac{T_0}{T} \right)\dot{Q} \tag{6}$$

$$\dot{X}_{work} = \dot{W}_{useful} \tag{7}$$

$$\dot{X}_{mass} = \dot{m}\psi \tag{8}$$

$$\psi = (h - h_0) - T_0(s - s_0) + \frac{V^2}{2} + gz \tag{9}$$

$$\dot{X}_{destroyed} = T_0 \dot{S}_{gen} \tag{10}$$

In the combustion process which does not involve any work, the maximum possible work, also known as reversible work is equal to the exergy destroyed and is calculated as follows:

$$\dot{W}_{rev} = \dot{X}_{destroyed} = \sum N_r\left(\bar{h}_f^o + \bar{h} - \bar{h}^0 - T_0\bar{s}\right)_r - \sum N_p\left(\bar{h}_f^o + \bar{h} - \bar{h}^0 - T_0\bar{s}\right)_p \quad (11)$$

$$\eta_I = \frac{W_{useful}}{Q_{input}} \quad (12)$$

$$\eta_{II} = \frac{W_{useful}}{W_{reversible}} = \frac{\eta_I}{\eta_{I,reversible}} = \frac{X_{recovered}}{X_{supplied}} \quad (13)$$

3 Exergy Analysis in Steam Turbine Power Plants

A lot of work on academic as well as research grounds has been done on the exergy analysis of steam turbine power plants. Systems ranging from simple to complex have been considered and locations of highest exergy losses have been highlighted. Even flow sheet software like Cycle-Tempo have been used to analyze complex systems involving several reheats and feed water heaters.

Regulagadda et. al. [3] have carried out an exergy analysis of a 32 MW coal fired thermal power plant. They have conducted a parametric study to determine how the system performs with different operating parameters. They noticed that most exergy destruction takes place in the boiler. They have also found that the efficiency increases with steam pressure and temperature and decreases with increase in condenser pressure. They suggest that decreasing the condenser pressure, optimization of heat transfer area and configuration, effective arrangement of the soot blowing system and better material selection of heat transfer surfaces could improve the efficiency. Also, combustion system improvement will lead to improving the overall performance.

Li and Liu [4] carried out exergy analysis on a 300 MW coal fired power plant. They found that the boiler is the largest exergy destroyer due to the inherent combustion and heat transfer processes. In the boiler-super heater, 72% of exergy is lost while in the reheater, 13% of exergy is lost. Turbines are responsible for only 6% exergy loss while condenser is for 3.8%. However, they did not suggest any specific modifications to improve the performance.

Kaushik et. al. [5] have reviewed the energy and exergy analyses of thermal power plants-both steam and gas turbine power plants (in combined cycle mode only). They have summarized the fundamental equations that are generally used for such a study. They too have concluded that in a steam turbine power plant, the boiler is the single most source of exergy destruction. They attribute this to incomplete combustion, improper insulation and entropy generation. However, they emphasized that certain inherent irreversibilities in the combustion processes cannot be taken care due to the limitation of the knowledge. In a case study, they have noticed that the energy and exergy efficiencies increase with increase in operating pressure and temperature.

Kamate and Gangavati [6] have carried out exergy analysis in a cogeneration power plant in a sugar industry. They attempted to optimize the plant and have evolved with the optimum operating conditions based on exergy performance. They found that the exergy efficiency increases with inlet steam pressure and temperature. For a condensing steam turbine plant, the energy and exergy efficiencies were found to be 68% and 26% while for a back pressure plant, they are 86% and 31% respectively. They too singled out the boiler to be the major source of exergy destruction. They calculated that only 37% of chemical energy of the fuel is being useful while the rest is lost in combustion irreversibilities.

Verkhivker and Kosoy [7] have carried out exergy analysis on a 232.6 MW steam power plant and found that the exergy efficiency is around 38%. They concluded that the principle irreversibilities are associated with the chemical transformation of exergy into heat, the subsequent transfer of this heat to the working fluid and the heat exchange. They proved that the exergy destruction can take place on increasing the steam temperature and pressure and by reducing the temperature difference in the heaters.

Suresh et. al. [8] have carried out an exergy analysis of a super critical power plant for Indian conditions. The obtained results have been used to train an artificial neural network program in order to minimize the fuel consumption for a given power output. They observed that there is a significant reduction in exergy loss in the combustor with the decrease in ash content of coals which is due to increase of combustibles. However, they noticed that the heat transfer irreversibilities in the boiler increases for low ash coals. This is due to the higher flue gas temperature using low ash coals. They also suggested that the exergy loss in the combustor may be a suitable indicator to determine the effect of variation in coal composition on the power plant performance.

Saidur et. al. [9] have focused on industrial boilers and conducted an energy and exergy analysis. They too found that the combustion chamber is the major contributor for exergy destruction followed by the heat transfer process. They have suggested to implement variable speed drives for boiler fans and heat recovery from flue gases to improve the boiler energy performance. Since a boiler in an important part of a steam turbine power plant, this study is directly useful to power plants and the suggestions made need to be implemented.

Zhang et. al. [10] have carried out an exergy based cost analysis on a 300 MW pulverized coal fired power plant in China. They proved that specific irreversibility cost is more suitable than the unit exergy cost in representing the production performance of a component.

Suresh et. al. [11] have replaced the feed water system of a sub-critical and a super-critical coal fired steam turbine power plant. This resulted in 14-19% reduction of coal consumption. This is due to reduction of head addition at low temperature. This also reduces the amount of CO_2 released into the atmosphere. However, an economic analysis showed that using solar water heaters in place of feed water heaters is not economically viable, at least as on date (2010). However, with improvement in technology and materials, it could be practically possible and result in reduction of fossil fuel consumption.

Aljundi [12] performed an energy and exergy analysis on a 396 MW steam power plant in Jordan. The aim was to identify the sites of energy and exergy losses. Also, the influence of reference state on the exergy analysis was studied. He too found that maximum exergy destruction takes place in the boiler, followed by the turbine and condenser. Also, the inherent irreversibilities in the combustion process were identified to cause much exergy loss. To mitigate this, he suggested that the combustion air needs to be pre-heated and the excess air needs to be reduced. The influence of the moderate changes of the reference state had almost no influence on major performance parameters.

Tsatsaronis et. al. [13] have focused only on the combustion aspects and set out on quantifying the irreversibilities/inefficiencies involved in a combustion process. Combustion inefficiencies are a result of chemical reaction, heat transfer, friction and mixing. They have divided the total exergy destruction as endogenous and exogenous, i.e. the one within the system of interest and the other caused due to irreversibilities in adjacent systems. It was understood that most of the irreversibilities in combustion can’t be avoided. Avoidable part of exogenous and endogenous irreversibilities need to be curbed. The latter can be reduced by changes in the combustion system. Finally, they conclude saying that to optimize the system, the entire system must be considered and not just the combustor even though most exergy destruction takes place there.

Dincer and Al-Muslim [14] have carried out an energy and exergy analysis of a Rankine cycle with reheat steam power plant and conducted studies on 120 cases obtained by varying the operating parameters like steam temperature, pressure, mass fraction ratio and work output. They found their results to be matching with the real world values. The exergy efficiency was found to increase with steam temperature and pressure. Exergy efficiency was found to be decreasing with increase in mass fraction feeding regenerator.

Kaska [15] carried out an energy and exergy analysis on an organic Rankine cycle which derives waste heat from a steel industry. They found that evaporator (boiler) has maximum exergy destruction followed by turbine, condenser and pump. It was also found that increasing the evaporator pressure increases the energy and exergy efficiencies. Pinch point analysis too is performed to determine the influence of heat exchange process on the power output.

Peng et. al. [16] have carried out an exergy analysis on a 300 MW solar hybrid coal fired power plant in China. Solar energy was used to heat the feed water instead of steam. They compared it with solar only power generation facility. It was found that the exergy destruction of solar hybrid plant is lower than solar only plant. Also, the hybrid plant had better off design parameters compared to solar only plant.

Adibhatla and Kaushik [17] have carried out energy and exergy analysis of a 660 MW coal fired super critical power plant at various load conditions. They found that the boiler has the maximum amount of exergy destruction followed by the turbine. Moreover, the sliding pressure operation at part loads was found to be better than constant pressure operation, from the exergy destruction view point.

Sandhya et. al. [18] have carried out an exergy analysis on a 422 MW coal fired ultra super critical power plant. The exergy loss was found to be highest at 86%

in the furnace. The turbine has an exergy efficiency of 82% while the condenser was at 70%. This isolates the furnace and boiler as the single culprit of exergy destruction. They have carried out simulations to utilize the exhaust heat in the flue gases to preheat air and fuel and found that the exergy loss dropped to 71% from a whopping 86%.

Ege and Sahin [19] have performed an uncertainty analysis on the energy and exergy analysis of power plants. They found that for various loads between 40-100%, the energy efficiency varied from 1.82-1.98% and the exergy efficiency varied from 1.32-1.43%. Most importantly, they found that determining the lower heating value (LHV) is the single most important parameter affecting the sensitivity of the energy and exergy analyses.

Hanak et. al. [20] have carried out an exergy analysis of a super-critical high ash coal fired power plant with carbon capture process. The exergy analysis revealed that integrating the supercritical coal fired power plant with the monoethanolamine post combustion capture and the CO_2 compression unit results in 8.6% exergy efficiency penalty. This was, however, marginally increased by introducing the waste heat recovery system resulting in reduction of the overall exergy destruction. Also, having analyzed the locations resulting in the highest exergy destruction, it was identified that the exergy losses can be partially avoided through desuperheating the reboiler steam in one of the HPFWHs, utilizing the stripper condensate and the CCU waste heat for district heating, and through the introduction of intercooling in the absorber.

Dincer and Rosen [21] have compiled the methods and results of energy and exergy analysis of various energy systems and industries. They also have made plenty of suggestions to improve the exergic performance of all the energy systems that they have dealt with.

Table 1 summarizes the amount of exergy destruction in various important components of a steam turbine power plant. It clearly suggests that maximum destruction takes place in the boiler due to the combustion and heat transfer processes. Hence all the attention towards performance improvement must be focused on the boiler rather than the condenser, which would have been suggested by an energy analysis.

Table 1: Exergy Destruction (%) in Boiler, Turbine and Condenser

	Regulagadda (32 MW)	**Li and Liu (300 MW)**	**Verkhivker, Kosay (232 MW)**	**Aljundi (396 MW)**
Boiler	87	85	52	77
Turbine	7.5	6	4	13
Condenser	2	3.8	0.42	9

4 CONCLUSIONS

In all the studies, the furnace cum boiler which carries out the combustion and heat transfer process turns out to be the site of maximum exergy destruction. Moreover, the inherent irreversibilities in the combustion process itself are high in magnitude. The other components of notable exergy destruction are the turbine, condenser and pump. As on date, there is no technology available to mitigate the combustion irreversibilities while some steps can be taken in improving the combustion conditions.

To improve the performance of Steam Turbine Power Plants, the following suggestions have been made based on the recommendations found in the literature:

Low Cost modifications:

i. At full load, the steam temperature and pressure should be at the highest limit while at part load, they must be reduced.
ii. Prevent leaks of steam, air, gas in the circuit.
iii. Utilize automated controls to operate at design specifications and to predict future problems.
iv. Periodic overhaul of devices.

Combustion Related Improvements:

i. The combustion reactions inherently have irreversibilities and hence cannot be minimized.
ii. Reduce incomplete combustion by providing better fuel-air contact.
iii. Reduce excess air to minimize the thermal losses in flue gases.
iv. Preheat the combustion air using flue gases or low pressure bled steam.
iv. Modifications to the burners and combustion chamber can reduce combustion losses.
v. Combustion losses can be further reduced if high temperature resistant materials are available which permit high temperature combustion.

Heat Transfer Related Improvements:

i. Usage of soot blowers to keep the heat transfer surfaces clean.
ii. Employing Fluidized Bed Combustion and immersing the heat exchanger surfaces in the bed results in high heat transfer rates (~300-500 W/m^2-K).
iii. Increasing the operational pressure and degree of superheat will increase the mean temperature of heat addition and reduce moisture towards turbine outlet.
iv. Heat recovery from the flue gases.
v. Improving the heat transfer rates by innovative methods like improvement in surfaces.
vi. Reheating increases the mean temperature of heat addition and hence decreased irreversibilities.
vii. Implementing regeneration also increases the mean temperature of heat addition and reduces the heat input. This improves efficiency even though the net work decreases.
vii. Heat transfer must take place across small temperature differences. This will result in large and expensive heat transfer surfaces and hence economic studies must be involved in this field.

Other Sources of Improvement:

i. Improving the expansion and compression device efficiencies.
ii. Incorporating sliding pressure operation wherever throttling is occurring.
iii. Part load operation must be carried out at sliding pressure rather than constant pressure.
iv. The condenser pressure can be suitable reduced to carry out greater amount of expansion.
v. The combustion process itself may be replaced with a more efficient energy recovery process, like using a fuel cell.
vi. Install variable speed drives in the boiler fans' motors to save energy.

NOMENCLATURE

Symbol	Name
$\dot{E}$	Rate of energy transfer (power), kW
g	Acceleration due to gravity=9.81 m/s^2
h	Enthalpy, kJ/kg
h_0	Enthalpy at dead state, kJ/kg
$\dot{m}$	Mass flow rate, kg/s
$\dot{Q}$	Rate of heat transfer, kW
S	Entropy, kJ/kg-K
S_0	Entropy at the dead state, kJ/kg-K
T	Temperature, K
T_0	Temperature at the dead state, K
V	Velocity, m/s
$\dot{W}$	Rate of work (power), kW
$\dot{X}$	Rate of Exergy Transfer, kW
z	Height, m
η	Efficiency
η_I	First law efficiency or Thermal efficiency
η_{II}	Second law efficiency

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