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Research Article

Exergy Analysis of the Turbine for a Reheat Regenerative 210 MW Fossil-Fuel based Power Plants in India

Shailendra Pratap Singh[A*] and Vijay Kumar. Dwivedi[B]

[A]Department of Mechanical Engineering, Inderprastha Engineering College, Ghaziabad, State Uttar Pradesh, Country India
[B]Department of Mechanical Engineering, , Galgotia College of Engineering & Technology, Greater Noida State Uttar Pradesh, Country India

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Abstract

In this study, the exergy analysis has been applied to the typical 210MW (LMZ) in India. The fuel used in this power plant was low calorific value sub bituminous coal. The irreversibility rates (or exergy destruction rates) of each cylinder of turbine are obtained for different ambient temperatures by the exergy analysis. The ambient temperature was selected within the range of 5–45^{0}C. The percentage efficiency defects of each turbine (or the ratios of the irreversibility rates to the fuel exergy rate) and the exergy efficiencies were determined for different ambient temperatures. Exergy parameters steam turbine cylinders have been determined to compare the actually achieved performance parameters with ideal performance parameters, which are not achievable indeed but these are authentically comparable. Increased destruction of exergy of any component shows that it has better scope of improvement. This thermodynamic analysis technique provides more meaningful results than the energy analysis, and pinpoints the locations and causes of inefficiencies more accurately. This procedure for the exergy analysis of the power plant could be applied to the different thermal applications for optimization and design purposes.

***Keywords**: Exergy; Irreversibility, Exergy efficiency, Efficiency defect; Steam power plant*

1. Introduction

India's energy market is one of the country's fastest developing sectors. Annual demand for electricity has increased from 1713 MW in 1950 to 2,25,793.10 MW(31.06.2013).The electricity generated from thermal power plants constitutes 68.14 % of total generation. The availability of coal in the country is such that the higher grades of coal, which have higher calorific value, have been exhausted and progressively lower grades of coal are being made available for generation of electricity in power plants. This had resulted in poor thermal efficiencies of power plants. Shortage of power is being felt from all corners of India and National Electricity Policy (NEP) stipulates the power for all by 2012. To fulfill the objective of NEP, a capacity of 79,200 MW would be required to be added in the country during 13th Plan. This growing demand of power all over the world has made the power plants of scientific interest and also for the efficient utilization of resources. This has led to development of various analysis techniques for improving the performance of power plants. The most commonly used method for the analysis is the First Law of Thermodynamics. However there is increasing interest in the combined utilization of first and second law of thermodynamics, using the concepts such as exergy and exergy destruction in order to evaluate the efficiency with which the available energy is consumed. Exergy analysis provides the tool that provides the distinction between the energy losses to the environment and internal irreversibilities in the processes [Moran M J, (1989)].

The exergy balance of system allows us to allocate and calculate irreversibilities in the production process and to identify which units and what for reason they affect the overall efficiency. In recent years the second-law based exergy analysis of thermal power plants has increasingly attracted engineer's attention [Szargut J et al. (1987), Kotas T J (1985), Bejan et al.(1996)]. Engineers and scientists have been applying first law to calculate enthalpy balances for more than a century to quantify the loss of efficiency in a process due to loss of energy. An exergy assessment allows one to quantify the loss of efficiency in a process due to loss of quality of the energy. This analysis can indicate where the process can be improved and, therefore, what areas should receive more attention. The exergy analysis sometimes referred to in literature as thermodynamic availability, available energy or useful energy.

The majority of the causes of thermodynamic imperfection of thermal and chemical processes of thermal power plants cannot be detected by means of an energy analysis. For example, irreversible heat transfer, throttling, and adiabatic combustion are not associated with any energy loss, but they lead to decrease the energy quality, reducing its ability to be transformed into other kind of energy and therefore increase the operational cost of

*Corresponding author: **Shailendra Pratap Singh**

installation. These effects of the aforementioned irreversible phenomenon can be detected and evaluated by only second law of thermodynamics. The main purpose of the exergy analysis is to detect and evaluate quantitatively the causes of the thermodynamic imperfection of thermal processes. The exergy analysis can therefore give the information about the possibilities of improving thermal processes, but cannot state whether or not the possible improvement is practicable. Such a question can be answered only by the economic analysis. Recently a large number of studies based on exergy analysis have been carried out by the researchers [Aljundi I H (2009), Bejan and A (1988)] to evaluate the thermal power plants at designed and operating conditions and gas turbines. A recent research in exergy analysis has been discussed (Tsatsaronis (2007), Regulagadda, P. *et al* 2013, Hasan Huseyin Erdem *et al* 2009 and2010).

2. Energy and Exergy analysis

The mass and energy conservation laws have been applied to each component and also for whole system. The energy and exergy analysis for the base condition of 210MW has been performed to pinpoint the location and magnitude of process irreversibilities. Further, the deviation of first and second law efficiency has been estimated.

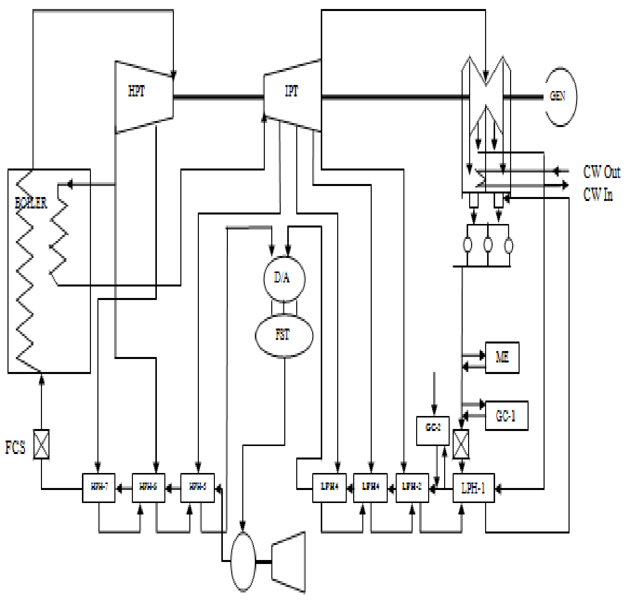

Figure 1- Process flow diagram for the unit chosen for analysis

The major streams entering and leaving the components of the plant are shown in the Figure 1 .To identify the sources of the availability destruction, the entire plant has been split into different control volumes, viz. Boiler with its inputs and outputs, generator, condenser and regenerative system and the entire cycle with boiler, turbine, generator, condenser and regenerative system. This would help to find out the individual contribution towards the gross irreversibility of the plant, as well as, the response of different parts towards exergy destruction with base and operating conditions. A general energy and exergy-balance equations, applicable to any component of a thermal system may be formulated by using the first and second law of thermodynamics; the specific thermo-mechanical exergy (neglecting kinetic and potential energy) is evaluated from

$$\epsilon_j = Q \times \left[(h_j - h_o) - T_0(s_j - s_o)\right]$$

where the Q, j ,h, s and 0 denotes mass flow rate of stream, energy or exergy flow streams entering or leaving the component at any point, specific enthalpy, specific entropy and thermodynamic properties at ambient conditions respectively in above Equations. A detailed exergy analysis includes calculating the exergy destruction and loss in each component. The exergy balance equation for any component (without decomposing)

$$\sum_{k=0} E_{e.k} + W_K = E_{q.k} + \sum_{k=0} E_{i.k}$$

The subscripts e, i, k and q denote exit, inlet, component and heat transfer respectively. E & W denote the Exergy rate and work transfer rate

The exergy destruction rate in a component is calculated from exergy balance

$$\epsilon_d = \sum_i E_{i.k} - \sum_e E_{e.k}$$

The efficiency defect is the percentage ratios of irreversibility rates to fuel exergy rate.

$$\text{Efficiency defect} = {\epsilon_d}/{\epsilon_f} = {\text{Exergy Destruction rate}}/{\text{Fuel exergy}}$$

The general definition for exergetic efficiency for a thermal system is

$$\text{Exergetic Efficiency} = {\epsilon_d}/{\epsilon_{in}} = {\text{Exergy Destruction rate}}/{\text{All input exergy}}$$

3 System Description and assumptions

210 MW LMZ plant consists of HP, IP and LP turbines with reheating. Steam after expanding in LP turbine is exhausted in condenser. The condensed steam passes through the LP and HP regenerative feed water heaters. The hot water is then fed to boiler drum through the economizer. Cycle has been analyzed with following assumption.

- Specific exergy of fuel has been calculated as in Bejan et al. [20].
- Gross calorific value has been used in calculations.
- Intensive properties of the environment are not changing due to any process.

4. Exergy analysis of the Turbine

4.1 High Pressure Turbine

Shaft power or work done by the turbine in totality or by any of the three separate rotors is not measured and monitored. Required governing equations for the analysis of exergy are mentioned here under;

$\epsilon_{rec,HPT} = Q_{ms} \times (H_{ms} - H_7) + (Q_{ms} - q_7) \times (H_7 - H_{crh}) - T_0 \times [Q_{ms} \times (S_s - S_7) + (Q_{ms} - q_7) \times (S_7 - S_{crh})]$

$\epsilon_{rec} = \epsilon_{in} - \epsilon_{out}$

$\epsilon_d = \epsilon_{in} - \epsilon_{out} - W_{Turbine}$

$\eta_{II,Turbine} = 1 - {}^{\epsilon_d}/_{\epsilon_{in} - \epsilon_{out}}$

4.2 Intermediate Pressure Turbine

Reheated steam expands through the intermediate turbine, from which steam is removed for various feed heaters and reduces the exergetic potential to it. Required governing equations for the analysis of exergy are mentioned here under;

$\epsilon_{rec,IPT} = Q_{hrh} \times (H_{hrh} - H_5) + (Q_{hrh} - q_5 - q_d) \times (H_5 - H_4) + (Q_{hrh} - q_5 - q_d - q_4) \times (H_4 - H_3) + (Q_{hrh} - q_5 - q_d - q_4 - q_3) \times (H_3 - H_2) - T_0 \times [Q_{hrh} \times (S_{hrh} - S_5) + (Q_{hrh} - q_5 - q_d) \times (S_5 - S_4) + (Q_{hrh} - q_5 - q_d - q_4) \times (S_4 - S_3) + (Q_{hrh} - q_5 - q_d - q_4 - q_3) \times (S_3 - S_2)]$

$\epsilon_{rec} = \epsilon_{in} - \epsilon_{out}$

$\epsilon_d = \epsilon_{in} - \epsilon_{out} - W_{Turbine}$

$\eta_{II,Turbine} = 1 - {}^{\epsilon_d}/_{\epsilon_{in} - \epsilon_{out}}$

4.3 Low Pressure Turbine

Expansion of steam produces large volumetric changes at low pressure, which proportionately changes the work potential of the steam. Advantage of high volume change at low pressure, significantly set aside due the poor dryness fraction of the steam at last stages of the low pressure turbine and this factually leads to the lower efficiency of the last cylinder of the steam turbine. Required governing equations for the analysis of exergy are mentioned here under;

$\epsilon_{rec,LPT} = Q_{LPT} \times (H_{LPT} - H_1) + (Q_{LPT} - q_1) \times (H_1 - H_{bu}) - T_0 \times [Q_{LPT} \times (S_{LPT} - S_1) + (Q_{LPT} - q_1) \times (S_1 - S_{bu})]$

$\epsilon_{rec} = \epsilon_{in} - \epsilon_{out}$

$\epsilon_d = \epsilon_{in} - \epsilon_{out} - W_{Turbine}$

$\eta_{II,Turbine} = 1 - {}^{\epsilon_d}/_{\epsilon_{in} - \epsilon_{out}}$

Exergy supplied to all the three cylinders has been separately mentioned in above referred equations but in actual practice it can be made of some practical significance only when viewed as the integral input to turbo alternator and electricity generated at the generator terminals. In all calculation Exergy supplied to the boiler by the fuel at T_{fg}=1500K is 425758 KJ/Sec.

Table 1(a) Exergy Supplied to the turbine by the steam at T_0=298 K

Turbine	Flow	Press.	Temp.	Enthalpy	Entropy
	Kg/sec	bar	^{0}C	KJ/Kg	KJ/Kg K
	$Q_{MS/HRH/LPT}$			$H_{MS/HRH/LPT}$	$S_{MS/HRH/LPT}$
HPT/MS	171.57	127.886	530	3420.86	6.55
IPT/HRH	150.59	22.803	530	3531.87	7.45
LPT	123.06	1.23754	172	2818.75	7.61
	$Q_{CRH/bu}$			$H_{CRH/bu}$	$S_{CRH/bu}$
CRH	150.59	25.3313	314	3036.02	6.7
Cond.	121.02	0.10191	46	2389.25	7.7901

Table 1(b) Exergy Supplied to the turbine by the steam at T_0=298 K

Turbine	Ex rec	$W_{Turbine}$	Ex Xd	Exergy Efficiency
	KJ/sec	KJ/sec	KJ/sec	
HPT	72679	61500	11178.8	0.846188
IPT	114810	102500	12310.5	0.892776
LPT	58931	41000	17930.6	0.695733
Exergy supplied by steam	246420	205000	41419.9	0.831913

Table 2 Parameters of RFH in estimation of exergy supplied to the turbine

H. E. No	Flow	Press.	Temp.	Enthalpy	Entropy
	Kg/Hr	bar	deg C	KJ/Kg	KJ/Kg K
	q_x			H_x	S_x
HPH7	7.7611	38.9462	369	3137.09	6.6
HPH6	11.653	25.3313	314	3044.38	6.7
HPH5	3.7542	11.9327	440	3339.82	7.5
D/A	3.9217	11.9327	440	3233.22	7.3
LPH4	7.4406	6.36282	368	3183.2	7.6
LPH3	5.4286	2.72987	252	2976.16	7.65
LPH2	6.5369	1.26312	172	2813.73	7.8
GC-2	1.3083	0.27545	316	3107.58	8.9
LPH1	2.3503	0.27141	67	2581.15	7.6835
GC-1	0.4611	0.19675	267	2948.66	8.6
ME	0.4167	0.24593	137	2756.71	8.2

Table 3(a) Irreversibility rates of the components for different T_0

System	278	283	288	293	298
HPT	10679.7	10804.5	10929.3	11054.1	11178.8
IPT	11348.5	11589	11829.5	12070	12310.5
LPT	17492.4	17602	17711.5	17821.1	17930.6
TOTAL	39520.6	39995.4	40470.3	40945.1	41419.9

Table 3(b) Irreversibility rates of the components for different T_0

System	303	308	313	318
HPT	11303.6	11428.4	11553.2	11678
IPT	12551	12791.5	13032	13272.5
LPT	18040.2	18149.7	18259.2	18368.8
TOTAL	41894.8	42369.6	42844.5	43319.3

Table 4(a) Exergy efficiency for different T_0

System	278	283	288	293	298
HPT	0.8520	0.8505	0.8491	0.8476	0.8461
IPT	0.9003	0.8984	0.8965	0.8946	0.8927
LPT	0.7009	0.6996	0.6983	0.6970	0.6957
TOTAL	0.8383	0.8367	0.8351	0.8335	0.8319

Table 4(b) Exergy efficiency for different T_0

System	303	308	313	318
HPT	0.8447	0.8432	0.8418	0.8404
IPT	0.8909	0.8890	0.8872	0.8853
LPT	0.6944	0.6931	0.6918	0.6905
TOTAL	0.8303	0.8287	0.8271	0.8255

Table 5(a) Efficiency defect rates of the components for different ambient temp.

System	278	283	288	293	298
HPT	0.0251	0.0254	0.0257	0.026	0.0263
IPT	0.0267	0.0272	0.0278	0.0283	0.0289
LPT	0.0411	0.0413	0.0416	0.0419	0.0421
TOTAL	0.0928	0.0939	0.0951	0.0962	0.0973

Table 5(b) Efficiency defect rates of the components for different ambient temp.

System	303	308	313	318
HPT	0.0265	0.0268	0.0271	0.0274
IPT	0.0295	0.03	0.0306	0.0312
LPT	0.0424	0.0426	0.0429	0.0431
TOTAL	0.0984	0.0995	0.1006	0.1017

5. Results and discussion

The regenerative reheat power plant used for the calculations was shown in layout mention above. The fuel used in the power plant boiler was low calorific value coal. The detailed exergy based analysis for T_0=298 K is tabulated in table 1 and parameters used from regenerative feed heating to calculate different exergies is shown in table 2. Exergy-based calculated results are given in Tables 3, 4 and 5 for the ambient temperatures between 278 and 318 K. As the ambient temperature is varied from 278 to 318 K, the irreversibility rates of the turbines are also increases. For a 40^0C increase in the ambient temperature, the % efficiency defects of the High pressure turbine, Intermediate pressure turbine and the low pressure turbine increased from 2.51 to 2.74, from 2.67 to 3.12 and from 4.11 to 4.31 respectively. Overall increase in the % efficiency defects is from 9.28 to 10.71. The % exergy efficiencies of the High pressure turbine, Intermediate pressure turbine and the low pressure turbine decreases from 85.20 to 84.04, from 90.03 to 88.53 and from 70.09 to 69.05 respectively. Overall decreases in the % exergetic efficiency from 83.83 to 82.55 respectively. The total irreversibility rate of the plant increased approximately from 39.52 to 41.42 MW due to the turbines. From this analysis, It was found that a 1^0C increase of the ambient temperature caused 0.047 MW increase in the total irreversibility rate of the plant.

6. Conclusion of exergy analysis

A study based on the exergy analysis was conducted for the investigation of the effect of the ambient temperature on the efficiency defects of components and the exergy efficiency of the turbine unit existing power plant. This analysis can be followed by analysis of different other components of power plant like boiler, regenerative feed heating system, condenser and pumps. During the evaluation of performance of a power plant, exergy analysis provides a better insight into the losses (irreversibilities) in electric power generation. The overall performance should be based on the second-law efficiency (exergy efficiency) rather than the first law (thermal efficiency). Energy analysis misleads in determining the inefficiencies (efficiency defects) of the system.

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List of Symbols, Abbreviation and Nomenclature

MS Main Steam
IPT Intermediate Pressure Turbine
HPT Pressure Turbine
LPT Low Pressure Turbine
HRH Hot reheat
CRH Cold reheat
HPH High Pressure Heater
RFH Regenerative Feed Heating
D/A Deaerator
LPH Low Pressure Heater
GC Gland Cooler
ME Main Ejector
Q_{MS} Mass flow of main steam
Q_{LPT} Mass flow at the inlet of LPT
Q_{HRH} Mass flow of steam through reheater
H_{MS} Enthalpy flow of main steam
H_{LPT} Enthalpy flow at the inlet of LPT
H_{HRH} Enthalpy flow of steam through reheater
S_{MS} Entropy flow of main steam
S_{LPT} Entropy flow at the inlet of LPT
S_{HRH} Entropy flow of steam through reheater
$W_{turbine}$ Work done by the respective turbine
q_x Flow Parameters of RFH
H_x Enthalpy of RFH
S_x Enthalpy of RFH components
X used either to show the no of heater or initial of components used in RFH