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Energy And Exergy Analysis Of Fully Condensing Steam Turbine At Various Steam Load Condition

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Abstract: The power is very vital factor for development of any nation. Energy resources are limited in stock and its present consumption rate is in increasing trend. There fore energy efficiency and energy conservation are prime important. More over the technology largely used today to produce electricity from coal causes significant negative environmental impacts. Energy and exergy analysis are used to analyse the performance of thermal systems. Energy analysis deals with quantity aspect whereas exergy analysis deals with quality and quantity aspects of energy. Exergy analysis focuses on magnitude and location of energy loss. In this analysis energy efficiency, exergy destructions, exergy efficiency and turbine heat rates are evaluated at 40%, 50%, 60%, 70 % and 80 % Maximum continuos rating condition of steam turbine. Analysis shows that operating turbine at 80 % MCR attract plant heat rate improvement by 1356.72 kJ/Kwh, which reduce environmental CO_2 emission by 1907.79 kg/h, SO_2 emission by 43.66 kg/h and ash generation by 122.58 kg/ h.
Keywords: Energy efficiency; Exergy efficiency; Exergy destruction; CO_2 emission; Heat rate; Steam Turbine; SO_2 emission.

I. Introduction

The steam power plant supply 57 % of total power demand in India. The Coal being the major source of energy to produce steam and to generate power in steam power plant.The energy conversion efficiency of steam power plant is low and while burning coal creates environmental emissions[1].Therefore efficiency enhancement of coal to electric power generation is major issue of steam power plant. Inefficient use of coal not only waste resource but create environmental pollution issues such as CO_2, SO_2 and NO_X emissions. Hence energy conservation is paramount important.

Energy Conservation mainly focused energy efficiency. The first law of thermodynamics is normally used to analyze the energy utilization, but it doesn't use the quality aspect of energy. Exergy is the consequent of second law of thermodynamics. It is a property that enables us to determine the useful work potential of a given amount of energy at some specified state. A thorough understanding of exergy and the insights it can provide into the efficiency, environmental impact and sustainability of energy systems. Exergy analysis has been widely used in design, simulation and performance evaluation of thermal and thermo-chemical systems[2,3].

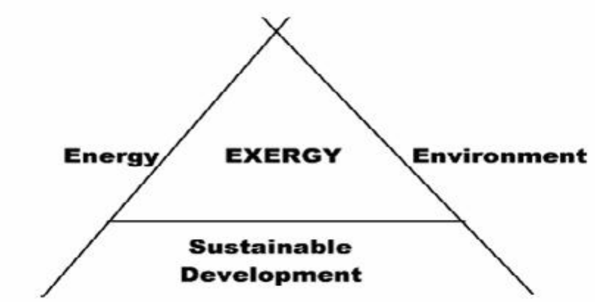

Fig.1 Interdisciplinary triangle covered by exergy analysis[4]

Steam power plant working on rankine cycle. This utilizes steam as a working medium to produce electrical power. This ideal cycle is friction less and not having any internal irreversibility. Rankine Cycle consists of the following four processes: isobaric heat addition in a boiler, isentropic expansion in a turbine, isobaric heat rejection in a condenser, and isentropic compression in a pump[5].

Superheated steam is produced in a boiler by utilizing the heat of combustion process. Assuming an open system, the high pressure forces the steam to the turbine where it expands isentropically and we get work by the rotation of the turbine shaft. The turbine is coupled with gear speed reducer and out put shaft of gear speed reducer is again coupled to electric generator. So by rotation of turbine shaft, generator rotate and electrical power is produced. The steam then exhausted into a condenser, where cooling medium absorbs the latent heat of steam and convert it to a saturated liquid (Condensate)[5]. In actual rankine cycle, the expansion of steam in steam turbine is not isentropic due to various internal irreversibilities. There fore entropy generation during steam expansion process ceases the second law efficiency.

Steam turbine system is usually analyzed by energy analysis which uses first law, in this analysis energy efficiency and plant heat rate are worked out. But better understanding is attained when a more complete thermodynamic view is taken, which utilises ***the second law analysis (Exergy Analysis)*** [6].

This study is focused on energy and exergy analysis of 22 MW fully condensing Steam Turbine. Energy efficiency, Plant heat rate, Exergy destruction and Exergy efficiencies are worked out at different load conditions such as 40%, 50%, 60%, 70 % and 80 % Maximum continuous rating condition of steam turbine. The effect of turbine heat rate improvement on coal consumption, ash generation, environment pollution such as CO_2 and SO_2emissions are also discussed.

II. Methodology

This section presents equations for energy and exergy analysis.It also present schematic diagram (Fig.2) and experimental data (Tab. 1).

1. Energy And Exergy Efficiency Relations

The expression of energy efficiency (First law efficiency - η_I) and exergy efficiency (Second law efficiency - η_{II}) for the fully condensing steam turbine are based on the following definitions,

First Law Efficiency, $\eta_I \% = (\dot{E}_{in} - \dot{E}_{out}) / \dot{E}_{in}$ (1)

Exergy Efficiency, $\eta_{II} \% = \Psi_{out} / \Psi_{in} = (\Psi_{power}) / \dot{m}_i (h_i - T_o S_i)$ (2)

Exergy Destruction , $\Psi_d = \Psi_{in} - \Psi_{out} - \Psi_{power}$ kJ/s (3)

2. Plant Heat Rate Considering Boiler Efficiency

$HR = \dot{m}_i (h_i - hw) / (Power \times \eta_{Boiler})$ kJ/Kwh (4)

3. Coal Saving

Coal saving =HR Improvement x Gen.Power / GCV (5)

4. Co2 Emmision Reduction

CO_2 emission reduction =3.66 x % C_{coal} x Coal saving kg/h (6)

5. So2 Emmision Reduction

SO_2 emission reduction =2 x Sulphur % in coal x Coal saving kg/h (7)

6. Ash Generation Reduction\

Ash Gen. Reduction = Coal saving x % ash in coal kg/h (8)

7. The Reference Environment

Exergy is always evaluated with respect to a reference environment. The reference environment is in stable equilibrium, acts as an infinite system, and is a sink or source for heat and materials, and experience only internal reversible processes, in which its intensive properties (i.e. temperature T_0, pressure P_0) remains constant. In this analysis surrounding temperature and pressure are taken as $T_0=34^0C$ and $P_0=101.325$ kPa as based on weather and climate condition at Bhavnagar, Gujarat (India).

8. Data of Steam Turbine

Data for study is taken at 40%, 50%, 60%, 70 % and 80 % MCR (Maximum Continuous Rating) of Fully Condensing Steam Turbine working at ***Nirma Ltd., Bhavnagar, Gujarat.*** The boiler of this power plant is fired by coal blend having lignite (70%) & Indonesian coal (30%) and coal firing rate is 10.5 kg/s. The Ultimate analysis of coal blend is as follows, C - 44.65%, N2 - 1.21%, H2 - 3.06%, O2 - 10.8%, S - 1.87%, Ash - 10.5%, Moisture - 27.78% and GCV of coal is 4226 Kcal/kg (17664.68 kJ/kg).

Table I: Experimental Data of Steam Turbine

Sr. No.	Particular	Unit	Value at 40 % MCR	Value at 50 % MCR	Value at 60 % MCR	Value at 70 % MCR	Value at 80 % MCR
1	Main Steam Flow	Ton Per Hour	34.00	41.00	48.00	56.00	65.00
2	Main Steam Pressure	kg/Cm^2	109.00	107.00	109.00	107.00	101.00
3	Main Steam Temperature	^0C	497.00	493.00	496.00	497.00	494.00
4	Enthalpy of Inlet Steam	kJ / kg	3355.20	3347.30	3352.60	3357.70	3357.70
5	Entropy of Inlet Steam	kJ/kg K	6.53	6.53	6.53	6.55	6.57
6	Exhaust Steam Flow	Ton Per Hour	34.00	41.00	48.00	56.00	65.00
7	Exhaust Steam Pressure	kg/Cm^2	-0.92	-0.92	-0.91	-0.92	-0.90
8	Exhaust Hood (Steam) Temperature	^0C	44.50	44.56	46.50	45.50	48.30
9	Enthalpy of Exhaust Steam	kJ / kg	2341.80	2341.90	2345.80	2319.90	2313.60
10	Entropy of Exhaust Steam	kJ/kg K	7.41	7.41	7.39	7.32	7.25
11	Condensate (Feed Water) Enthalpy	kJ / kg	186.21	186.46	194.56	190.38	202.08
12	Turbine Power	KW	8881.96	11050.81	13219.66	15698.34	18590.14
13	Generator Power	KW	8600.00	10700.00	12800.00	15200.00	18000.00

Assumptions:

1. There is no steam loss across steam turbine.
2. Gear box efficiency as per manufacturer 98.40 %
3. Generator efficiency as per manufacturer 98.03 %
4. Boiler efficiency is 83.53 %
5. Condensate is reused as feed water in boiler.

9. Steam Turbine Main *Specifications*[7]

Manufacturer: Hang Zhou Steam Turbine Co. Limited, China
Model & Type: HNK/ 50/63/56
Nominal Rating: 20000 KW
Nominal Speed: 5408 rpm
Maximum allowable steam flow: 8100 kg/h
Maximum allowable steam temperature: 525^0C
Maximum allowable steam pressure: 110 bar

Maximum Power at Max. Steam flow: 2200 KW
Normal Exhaust steam pressure: -0.916 bar
Normal Exhaust steam temperature: 48.6^0C
Number of stages: (1+32) / (Impulse + Reaction)
Governor Manufacturer: Wood Ward
Governor Type: Electric & Hydraulic

10.Schematic Diagram of Steam Turbine

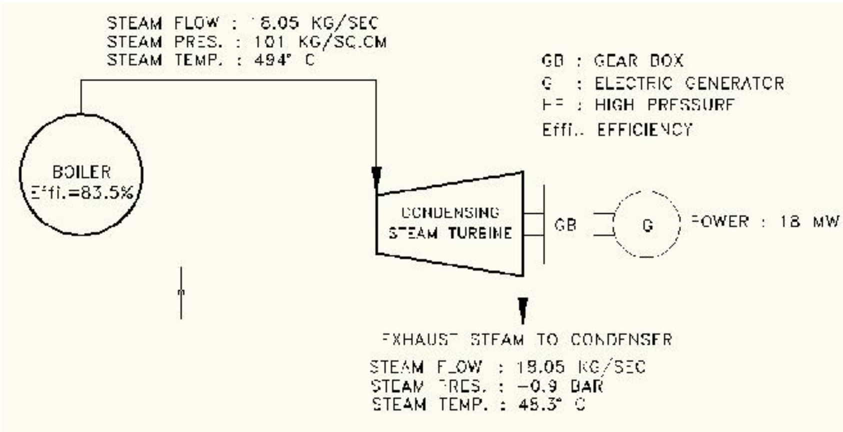

Fig.2 Process Flow Diagram of Condensing Steam Turbine

III. Calculation

Energy Calculation For 80 % Mcr

1. Energy Input :
   $\dot{E}_i = \dot{m}_i \times h_i$
   $= 65 \times 1000 \times 3357.70 / 3600 = 60625.13$ kJ/s.

2. Energy Output:
   $\dot{E}_o = \dot{m}_{exh} \times h_{exh}$
   $= 65 \times 1000 \times 2313.60 / 3600 = 41773.33$ kJ/s.

3. Work done:
   $W.D = \dot{E}_i - \dot{E}_o$
   $= 60625.13 - 41773.33 = 18851.80$ Kw
4. Actual Power develop by turbine:
   $P = \text{Generator power} \times \eta^{-1}_{gearbox} \times \eta^{-1}_{generator}$
   $= 18000 \times (0.984)^{-1} \times (0.9803)^{-1} = 18590.14$ Kw

5. Energy efficiency (First Law Efficiency) of turbine:
   η_I = Net Work done by turbine/ Energy input
   $= (\dot{E}_i - \dot{E}_o) / \dot{E}_i$
   $= 18851.80 / 60625.13 = 30.66$ %

6. Plant Heat Rate Considering Boiler Efficiency[8]
   HR = Net Heat Input /Generator Power
   $= 65 \times 1000 (3357.70 – 202.08) / 18000$
   $= 13642.15$ kJ/Kwh

7. Coal Saving due to Heat Rate improvement:
   Coal Saving = HR Improvement x Gen.Power / GCV
   $= 1356.72 \times 18000 / 17664.68$
   $= 1167.42$ kg/h

8. CO_2 emission reduction due to Heat Rate improvement:
   CO_2 emission reduction = 3.66 x % C_{coal} x Coal saving kg/h[9]
   = 3.66 x 0.4465 x 1167.42
   = 1907.7942 kg/h

9. SO_2 emission reduction due to Heat Rate improvement:
   SO_2 emission reduction = 2 x Sulphur % in coal x Coal saving kg/h[10]
   = 2 x 0.0187 x 1167.42
   = 43.66 kg/h

10. Ash Generation Reduction due to Heat Rate improvement:
    Ash Gen. Reduction = Coal saving x % ash in coal kg/h
    = 1167.42 x 0.105
    = 122.57 kg/h

Exergy Calculation For 80 % Mcr

1. Exergy Input :
   $\Psi_{in} = \dot{m}_i (h_i - T_0 S_i)$
   $= 18.06 (3357.70 -(307 \times 6.57)) = 24213.22$ kJ/s.

2. Exergy out :
   $\Psi_{out} = \dot{m}_{exh} (h_{exh} - T_0 S_{exh})$
   $= 18.06 (2313.60-(307 \times 7.25))$
   $= 1586.57$ kJ/s.

3. Exergy Destruction Steam Turbine :
   $\Psi_{des} = \Psi_{in} - \Psi_{out} - \Psi_{Turbine\ Power}$
   $= 24213.22 - 1586.57 – 18590.14 = 4036.51$ kJ/s.

4. Exergy Efficiency (Second Law Efficiency) of Steam Turbine :
   $\eta_{II} = \Psi_{power} / \Psi_{in}$
   $=18590.14 / 24213.22 = 76.78$ %.

IV. Result And Discussion

Table II: Experimental Result

	22 MW Condensing Steam Turbine					
S N	**Particulars**	**Value at 40 % MCR**	**Value at 50 % MCR**	**Value at 60 % MCR**	**Value at 70 % MCR**	**Value at 80 % MCR**
1	Energy Efficiency %	28.03	28.99	29.57	30.06	30.66
2	Exergy Destruction (kJ/sec)	3223.26	3470.83	3716.28	4151.94	4036.51
3	Exergy Efficiency %	69.73	72.30	73.59	74.82	76.82
4	Heat Rate (kJ/Kwh)	14998.88	14499.97	14177.72	13969.92	13642.16
5	Improved Heat Rate (kJ/Kwh)	0	498.91	821.16	1028.96	1356.72
6	Coal Saving kg/h	0	242.90	497.40	745.60	1167.42
7	CO_2 emission reduction kg/h	0	396.94	812.85	1218.44	1907.79
8	SO_2 emission reduction kg/h	0	9.08	18.60	27.89	43.66
9	Ash generation reduction kg/h	0	25.50	52.23	78.29	122.58

- The experimental result shows that as steam and power load on steam turbine increases its energy and exergy efficiency increases.
- Energy efficiency increased by 2.63 % and exergy efficiency by 7.09 % during 40 to 80 % MCR turbine operation.

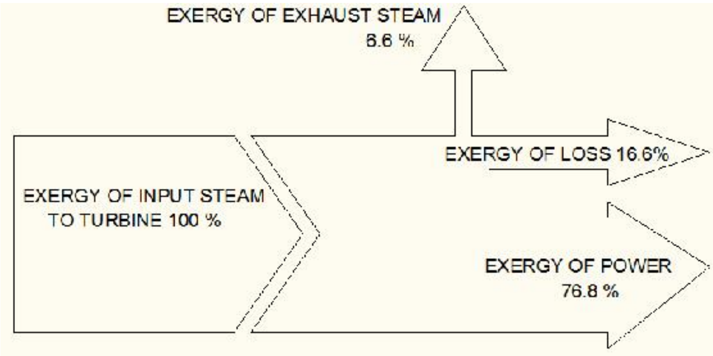

Fig.3 Grass man diagram for exergy flow through Steam Turbine at 80 % MCR

- The exergy destruction during 40 to 80 % MCR condition is increased by 813.25 kJ/s.
- The exergy destruction is mainly due to steam turbine irreversibilities.
- Real steam expansion process is away from ideal isentropic process in steam turbine due to internal friction.
- The energy efficiency is remarkably lower in all cases because leaving steam from turbine carrying considerable amount of energy that is purely waste in condenser.
- There is an improvement observed in plant heat rate by 1356.72 kJ/Kwh at 80 % MCR compare to 40 % MCR turbine operation.
- Coal saving is achieved due to this heat rate improvement by 1167.42 *kg/h.*
- Coal saving further reduced ash handling plant load by 122.58 *kg/h* and more improved life of plant because ash is highly erosive in nature. This creates mechanical wear during handling.
- Improved heat rate at 80 % MCR turbine operation lead to CO_2 emission reduction by 1907.79 kg/h and SO_2 emission reduction by 43.66 kg/h.

V. Conclusion

- Energy and exergy efficiencies are higher at higher MCR operation of turbine.
- Exergy loss is 25.30 % and 16.67 % as corresponding to 40 % and 80 % MCR turbine operation.
- Coal consumption reduced by 1167.42 *kg/h*
- Ash handling plant load reduced by 122.58 *kg/h*
- CO_2 emission reduced by 1907.79 *kg/h*
- SO_2 emission reduced by 43.66 *kg/h*

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