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Energy and Exergy Analysis of Extraction cum Back Pressure Steam Turbine

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Abstract: *Power is very vital factor for development of any society. Coal shares major chunk of fuels used to produce power in thermal power plants in India. Coal reserves are limited and present coal consumption rate is in increasing trend to fulfill the power demand. Therefore energy efficiency and energy conservation are of prime importance. Moreover, fossil fuel based power plant has significant negative environmental impacts. Energy and exergy analysis are used to analyze the performance of thermal systems. Energy analysis deals with quantity aspect whereas exergy analysis deals with quality aspect in addition to quantity. Exergy analysis focuses on magnitude and true location of energy loss. In this analysis, energy efficiency, exergy destruction, exergy efficiency and turbine heat rate are evaluated at 70 % and 85 % maximum continuous rating (MCR) of steam turbine. Analysis shows that operating turbine at 85 % MCR attract heat rate improvement by 17.01 kJ / kWh, which reduces CO_2 emission by 26.89 kg/h, SO_2 emission by 26.89 kg/h and ash generation by 41.47 kg/ day.*

Keywords: *Energy, Efficiency, Exergy, Exergy destruction, Power plant, Emission*

I. INTRODUCTION

Steam power plants supply 57 % of total power demand in India. Coal is the major source of energy in these power plants. The conversion efficiency from coal to electricity in steam power plants is low and combustion of coal has heavy negative impact on environment [1]. Efficiency enhancement of coal to electric power generation is major challenge against steam power plants. Thus, inefficient use of coal not only wastes resources but creates environmental pollution issues such as CO_2, SO_2 and NO_x emissions.

Energy conservation study is many times focused on energy efficiency. The first law of thermodynamics is used to analyze the energy utilization. First law analysis 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 in a given amount of energy at reference environmental state. A thorough understanding of exergy can provide insights into the efficiency, environmental impact and sustainability of energy systems. Exergy analysis is now widely used in design, simulation and performance evaluation of thermal and thermo-chemical systems [2, 3].

Cogeneration turbine systems, which produce heat at useful temperatures at the expense of reduced electrical power, have higher efficiencies than conventional steam turbine systems. The correct merit of cogeneration systems should be determined with the help of exergy analysis because energy analysis tends to overstate performance.

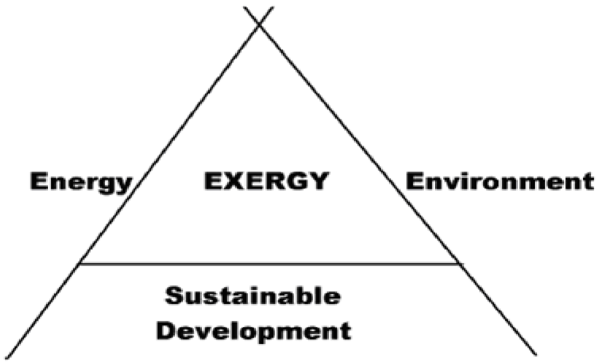

Fig.1 Interdisciplinary triangle covered by exergy analysis [4]

In the steam turbine under study, steam is first expanded from inlet pressure to extraction pressure in seven stages. The extracted high pressure and exhausted low pressure steam is being used in process heating of soda ash manufacturing. Remaining steam expands up to exhaust pressure. Steam turbine system is usually analyzed by energy analysis which uses first law analysis but better understanding is attained when a more complete thermodynamic view is taken, which utilises ***the second law of thermodynamics in conjunction with energy analysis, via exergy methods*** [5].

This study is focused on energy and exergy analysis of 20.6 MW Extraction cum Back Pressure Steam Turbine. Energy efficiency, exergy destruction and exergy efficiency are worked out at two different load conditions such as 70 % and 85 % of MCR. The turbine heat rate is also evaluated for both load conditions. The effect of turbine heat rate improvement on coal consumption and environment pollution such as CO_2 and SO_2 emissions are also discussed.

II. Methodology

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

1. Energy and second law efficiency (exergy efficiency) relations

The expressions of energy and exergy efficiencies for the extraction cum back pressure steam turbine (cogeneration) are based on the following definitions [6].

$$\eta_{I} = (\text{Actual Power Develop by Turbine Shaft}) / (\dot{E}_{in} - \dot{E}_{out}) \quad (1)$$

$$\eta_{II} = \Psi_{Power} / (\Psi_{in} - \Psi_{out}) = \Psi_{power} / [\, \dot{m}_i (h_i - T_o s_i) - (\dot{m}_o (h_o - T_o s_o) \,] \quad (2)$$

2. 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. It experiences 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 $T_0=34^0C$ (307 K) and $P_0=101.325$ kPa as based on weather and climate condition at Bhavnagar, Gujarat (India).

3. Data of Steam Turbine

Data for study is taken at 70 and 85 % MCR of Extraction cum Back Pressure 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 %, N - 1.21 %, H - 3.06 %, O - 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 70 % MCR	Value at 85 % MCR
1	Main Steam Flow	kg/s	40.75	43.05
2	Main Steam Pressure	kg/cm^2	104.9	107
3	Main Steam Temperature	^oC	492	497
4	Enthalpy of Inlet Steam	kJ/kg	3347.3	3357.7
5	Entropy of Inlet Steam	kJ/kg K	6.54	6.54
6	HP Extraction Flow	kg/s	22.47	18.33
7	HP Extraction Temperature	^oC	360.5	360
8	HP Extraction Pressure	kg/cm^2	34.48	34
9	Enthalpy of HP Ext. Steam	kJ/kg	3129.3	3129.1
10	Entropy of Inlet HP Ext.Steam	kJ / kg K	6.68	6.69
11	LP Extraction Flow	kg/s	18.28	24.72
12	LP Extraction Temperature	^oC	126	125
13	LP Extraction Pressure	kg/cm^2	1.6	1.72
14	Enthalpy of LP Exh. Steam	kJ / kg	2716.8	2712
15	Entropy of Inlet LP Exh. Steam	kJ / kg K	7.03	7.07
16	Generator Power	kW	13875	17100

Assumptions:
1. There is no steam loss across steam turbine.
2. Gear box efficiency as per the manufacturer is 98.40 %
3. Generator efficiency as per the manufacturer is 98.03 %
4. High pressure extracted steam and low pressure exhaust steam from turbine is utilised in process heating of soda ash manufacturing.

4. Steam Turbine Main Specifications

Manufacturer: Hang Zhou Steam Turbine Co. Limited, China
Model & Type: EHNG 50/40/50
Nominal Rating: 20600 kW
Nominal Speed: 5022 rpm
Normal first bled steam pressure: 35 bar
Normal first bled steam temperature: 366^{0}C
Normal exhaust steam pressure: 2.5 bar
Normal exhaust steam temperature: 133^{0}C
Number of stages: (1+23) / (Impulse + Reaction)
Governor manufacturer: Wood Ward
Governor type: Electric & Hydraulic

5. Schematic Diagram of Steam Turbine

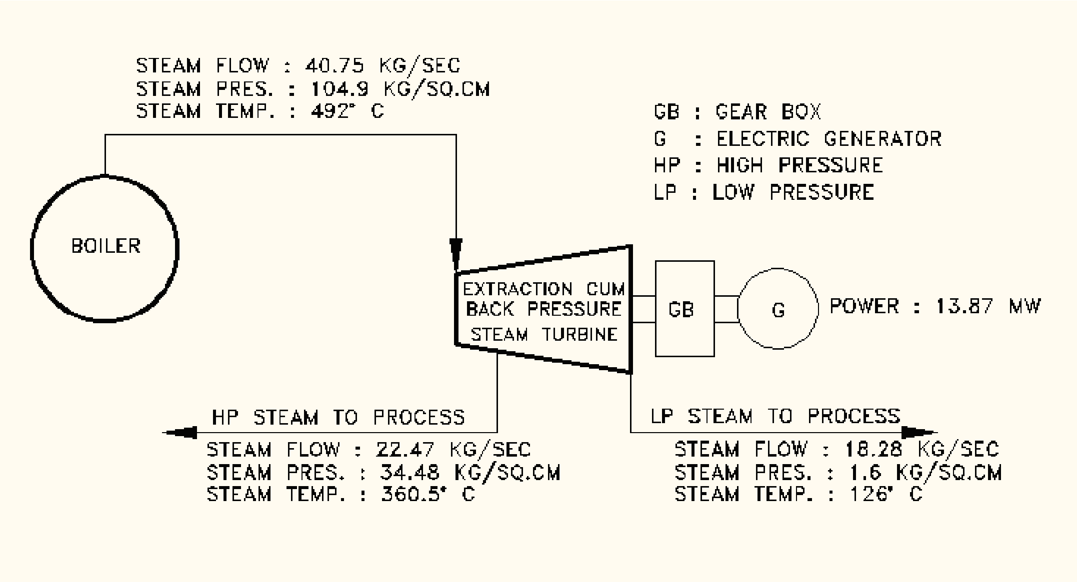

Fig.2 Process Flow Diagram of Steam Turbine

III. Analysis

A. ENERGY ANALYSIS FOR 70 % MCR

1. Energy input is equal to product of mass of steam into turbine and its enthalpy at entry.

$$\dot{E}_i = \dot{m}_i \times h_i \qquad (3)$$
$$= 40.75 \text{ kg/s} \times 3347.3 \text{ kJ/kg}$$
$$= 136402.475 \text{ kJ/s.}$$

2. Energy output is sum of heat extracted and heat exhausted.

$$\dot{E}_o = (\dot{m}_{ext} \times h_{ext}) + (\dot{m}_{exh} \times h_{exh}) \qquad (4)$$
$$= (22.47 \text{ kg/s} \times 3129.3 \text{ kJ/kg}) + (18.28 \text{ kg/s} \times 2716.8 \text{ kJ/kg})$$
$$= 119978.480 \text{ kJ/s.}$$

3. Work done is equal to the energy in steam at entry to turbine minus that at exit.

$$W.D = \dot{E}_i - \dot{E}_o \qquad (5)$$
$$= 136402.475 \text{ kJ/s} - 119978.480 \text{ kJ/s}$$
$$= 16424.00 \text{ kW.}$$

4. Actual Power Develop by Turbine Shaft :

$$P = \text{Generator Power} \times \eta^{-1}_{gearbox} \times \eta^{-1}_{generator} \qquad (6)$$
$$= 13875 \text{ kW} \times (0.984)^{-1} \times (0.9803)^{-1}$$
$$= 14380 \text{ kW.}$$

5. Energy Efficiency (1st Law efficiency) of Turbine :

η_I = (Actual Power Develop by Turbine Shaft) / ($\dot{E}_{in}$ - $\dot{E}_{out}$) (7)
= 14380 kW / (136402.475 kJ/s-119978.480 kJ/s)
= 87.56 %.

6. Heat Rate of Turbine [7] :

HR = Net Heat Input / Turbine Power (8)
= ($\dot{E}_i$ - $\dot{E}_o$) x 3600 s / 14380 kWh
= (136402.475 kJ/s - 119978.480 kJ/s) x 3600 / 14380 kWh
= 4111.71 kJ/kWh.

B. EXERGY ANALYSIS FOR 70 % MCR

1. Exergy Input :

$\Psi_{in} = \dot{m}_s (h_s - T_0 s_s)$ (9)
= 40.75 kg/s x [3374.3 kJ/s - (307 K x 6.54 kJ/kg K)]
= 55685.690 kJ/s.

2. Exergy Out :

$\Psi_{out} = \dot{m}_{ext} (h_{ext} - T_0 S_{ext}) + \dot{m}_{exh} (h_{exh} - T_0 S_{exh})$ (10)
= 22.47 kg/s x [3129.3 kJ/s - (307 K x 6.68 kJ/kg K)] +18.28 kg/s x [2716.8 kJ/s - (307 K x 7.03 kJ/kg K)]
= 34445.819 kJ/s.

3. Exergy Destruction in Turbine :

$\Psi_{des} = \Psi_{in} - \Psi_{out} - \Psi_{power}$ (11)
= 55685.690 kJ/s – 34445.819 kJ/s – 14380 kW
= 6859.87 kJ/s.

4. Exergy Efficiency (2nd Law efficiency) of Cogeneration Turbine :

$\eta_{II} = \Psi_{power} / (\Psi_{in} - \Psi_{out})$ (12)
= 14380 kW / (55685.690 kJ/s -34445.819 kJ/s)
= 67.70 %

C. ENERGY ANALYSIS FOR 85 % MCR

1. Energy input is equal to product of mass of steam into turbine and its enthalpy at entry.

$\dot{E}_i = \dot{m}_i \times h_i$ (13)
= 43.05 kg/s x 3357.7 kJ/kg
= 144548.985 kJ/s.

2. Energy output is sum of heat extracted and heat exhausted.

$\dot{E}_o = (\dot{m}_{ext} \times h_{ext}) + (\dot{m}_{exh} \times h_{exh})$ (14)
= (18.33 kg/s x 3129.1 kJ/kg) + (24.72 kg/s x 2712 kJ/kg)
= 124397.043 kJ/s.

3. Work done is equal to the energy in steam at entry to turbine minus that at exit.

W.D = $\dot{E}_i - \dot{E}_o$ (15)
= 144548.985 kJ/s -124397.043 kJ/s
= 20151.942 kW.

4. Actual Power Develop by Turbine Shaft :

P = Generator power x $\eta^{-1}_{gearbox}$ x $\eta^{-1}_{generator}$ (16)
= 17100 kW x $(0.984)^{-1}$ x $(0.9803)^{-1}$

= 17720 kW.

5. Energy Efficiency (1st Law efficiency) of Turbine :

η_{I} = (Actual Power Develop by Turbine Shaft) / ($\dot{E}_{in}$ - $\dot{E}_{out}$) (17)
= 17720 kW / (144548.985 kJ/s- 124397.043 kJ/s)
= 87.94 %.

6. Heat Rate of Turbine :

HR = Net Heat Input / Turbine Power (18)
= ($\dot{E}_i$ - $\dot{E}_o$) x 3600 / 17720 kWh
= (144548.985 kJ/s - 124397.043 kJ/s) x 3600 / 17720 kWh
= 4094.07 kJ/kWh.

D. EXERGY ANALYSIS FOR 85 % MCR

1. Exergy Input :

$\Psi_{in} = \dot{m}_s (h_s - T_0 s_s)$ (19)
= 43.05 kg/s x [3357.7 kJ/s - (307 K x 6.54 kJ/kg K)]
= 58114.05 kJ/s.

2. Exergy Out :

$\Psi_{out} = \dot{m}_{ext} (h_{ext} - T_0 s_{ext}) + \dot{m}_{exh} (h_{exh} - T_0 s_{exh})$ (20)
= 18.33 kg/s x [3129.1 kJ/s-(307 K x 6.69 kJ/kg K)] + 24.72 kg/s x [2712 kJ/s -(307 K x 7.07 kJ/kg K)]
= 33095.82 kJ/s.

3. Exergy Destruction in Turbine :

$\Psi_{des} = \Psi_{in} - \Psi_{out} - \Psi_{power}$ (21)
= 58114.05 kJ/s - 33095.81 kJ/s - 17720 kW
= 7298.24 kJ/s.

4. Exergy Efficiency (2nd Law efficiency) of Cogeneration Turbine :

$\eta_{II} = \Psi_{power} / (\Psi_{in} - \Psi_{out})$ (22)
= 17720 kW / (58114.05 kJ/s -33095.82 kJ/s)
= 70.83 %.

E. CO_2 AND SO_2 EMISSION REDUCTION BY TURBINE HEAT RATE IMPROVEMENT

1. Coal Saving = HR Improvement x Generator Power / GCV (23)
= 17.01 kJ/ kWh x 17100 kW / 17664.68 kJ/kg
= 16.46 kg/h.

2. Combustion Equation : $C + O_2 = CO_2$ (24)

3. 1 kg Carbon Generates 3.66 kg of CO_2 [8]

4. CO_2 Emission Reduction =3.66 x Carbon percentage in coal x Coal saving (25)

= 3.66 x 0.4465 x 16.46 kg/h

= 26.89 kg/h

5. 1 kg Sulphur Generates 2 kg of SO_2 [9]

6. SO_2 Emission Reduction = 2 x Sulphur percentage in coal x Coal saving (26)
= 2 x 0.0187 x 16.46 kg/h
= 0.62 kg/h.

F. ASH GENERATION REDUCTION BY TURBINE HEAT RATE IMPROVEMENT

1. Ash Generation Reduction = Coal saving x Ash percentage in coal (27)
= 16.46 kg/h x 0.105 = 1.72 kg/h x 24 h/day = 41.47 kg/day

IV. Result And Discussion

TABLE II
EXPERIMENTAL RESULTS

Sr. No	20.6 MW Extraction Cum Back Pressure Steam Turbine		
	Particulars	**Value at 70 % MCR**	**Value at 85 % MCR**
1	Energy Efficiency (%)	87.56	87.94
2	Exergy Destruction (kJ/s)	6859.87	7298.24
3	Heat input (kJ/s)	136402.475	144548.985
4	Useful heat output (kJ/s)	119978.480	124397.043
5	Turbine Work output (Kw)	14380	17720
3	Exergy Efficiency (%)	67.70	70.83
4	Heat Rate (kJ/kWh)	4111.71	4094.07
5	CO_2 emission reduction	26.89 kg/h	
6	SO_2 emission reduction	0.62 kg/h	
7	Ash generation reduction	41.47 kg/day	

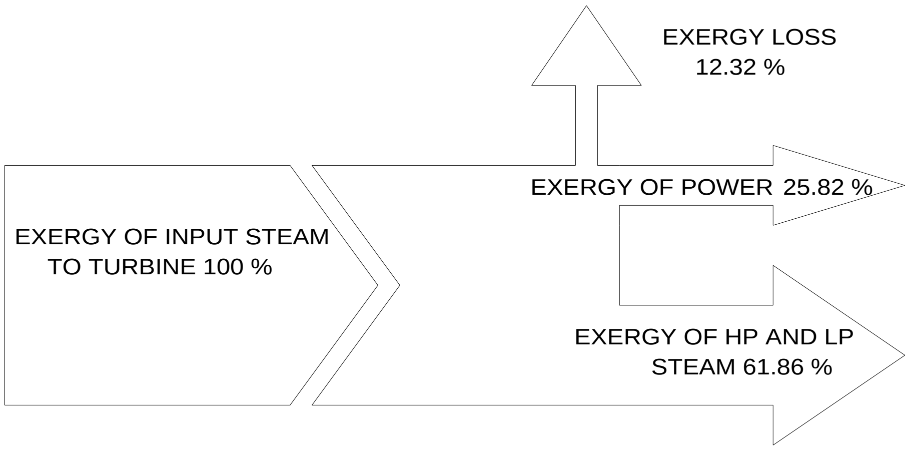

Fig.3 Grassman diagram for exergy flow through Steam Turbine at 70 % MCR

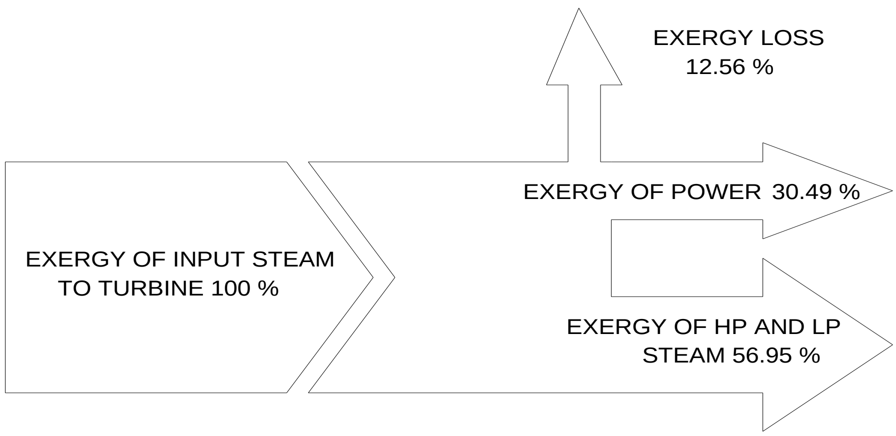

Fig.4 Grassman diagram for exergy flow through Steam Turbine at 85 % MCR

- **Experimental results show that as power load on steam turbine increases from 70 % to 85 % MCR**,

1. Turbine's energy and exergy efficiency increases by 0.38 % and 3.13 %.
2. The exergy destruction is increased by 438.34 kJ/s due to steam turbine irreversibilities and lower exergy output of HP and L.P.Steam.
3. The exergy efficiency is remarkably lower than energy efficiency in both the cases. This is mainly due to thermal product, which is higher than electrical power, is delivered at a lower temperature.
4. There is an improvement observed in turbine heat rate by 17.01 kJ/kWh.
5. Coal saving achieved due to heat rate improvement is 395 kg/day.
6. Ash handling plant load is reduced by 41.47 kg/day. This improves life of plant because ash is highly erosive in nature. It creates mechanical wear during handling.
7. Heat rate improvement lead to CO_2 emission reduction by 26.89 kg/h and SO_2 emission reduction by 0.62 kg/h.

V. Conclusion

Turbine exergy efficiency is lower than its energy efficiency as utilization of heat is at lower temperature than inlet. Turbine exergy loss is 12.32 % and 12.56 % at 70 % and 85 % MCR. When Turbine MCR is increased from 70 to 85%, coal consumption is reduced by 16.46 kg/h and ash handling plant load is reduced by 41.47 kg/day. CO_2 emission is reduced by 26.89 kg/h, while SO_2 emission is reduced by 0.62 kg/h. Thus, it is more advantageous to run turbine at higher MCR.

VI. Acknowledgment

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Nomenclature

$\dot{E}_i$ - Energy in [kJ/s], $\dot{E}_{out}$ - Energy out [kJ/s], Ψ_{in} - Exergy in [kJ/s], Ψ_{out} - Exergy out [kJ/s], Ψ_{des} - Exergy destruction [kJ/s] Ψ_{power} - Exergy of power [kJ/s], $\dot{m}$ - Mass flow rate [kg/s], h - Specific enthalpy [kJ/kg], s - Specific entropy [kJ/kg K], P -Turbine actual power [kW], T_0 -Atmospheric temperature [K], P_0 -Atmospheric pressure [kPa] , i - Inlet, o – Outlet, η_I - Energy efficiency [%], η_{II} - Exergy efficiency [%], HR- Heat rate [kJ/kWh], ext - steam extraction, exh - steam exhaust,

MCR - Maximum continuous rating, GCV - Gross calorific value [kJ/kg], C – Carbon, H – Hydrogen , O – Oxygen, N – Nitrogen, S – Sulphur, SO_2 - Sulphur dioxide, CO_2 - Carbon dioxide, NO_x - Nitrogen oxide, HP – High pressure, LP – Low pressure.

References

Web Page:

[1] Ministry of Power, Govt. of India, Web site,www.powermin.nic.in/Indian_electricity_scenario. (Accessed on 7 December 2012)

Journal Papers:

[2] Ganapathy T, Alagumurthi N, Gakkhar RP, Murugesan K. Exergy analysis of operating lignite fired thermal power plant. Journal of Engineering Science and Technology Review 2009; 2:123–30.

[3] Kanoglu, M, Dincer, I, Rosen, M A., 2007, "Understanding energy and exergy efficiencies for improved energy management in power plants". Energy Policy 35, 3967–3978.

[4] Rosen, M.A., Dincer I.2001.Exergy as the confluence of energy, environment and sustainable development .Exergy, an International Journal 1(1), 3-13.

[6] Sanjay Y., Singh O., and Prasad B.N., 2007, "Energy and Exergy Analysis of Steam Cooled Reheat Gas Steam Combined Cycle," Applied Thermal Engineering, 27, pp. 2779-2790.

Chapters in Books:

[5] I.Dincer and M.Rosen,"Energy, Exergy and Sustainable Development", Elsevier, 2007, Chap- 12,257-265

[7] Bureau of Energy Efficiency, Ministry of Power Govt. of India, Energy Auditor guide book volume- 4,2005,Chap-3,45-53.

[8] P Chattopadhyay,"Boiler Operation Engineering", 2nd edition, McGraw-Hill, 2000, Chap-10,314.

[9] N.C.Pandya and NC.S.Shah, "Heat Engines", 9th edition, Charotar Publishing House, Anand, 1990, Chap-13,594.