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Energy-Exergy Analysis of Combined Reheating-Regenerative Rankine Cycle using Entropy Generation Principle

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***Abstract:** The growing attention towards the exergy analysis of thermal systems is identifying the cause of losses, to scale the process, and rectifying the components. In this paper, the thermodynamic (energy-exergy) analysis of combined reheating and regeneration based Rankine Cycle is carried out. The energy-exergy analysis has been established for the boiler, turbines, Feed heaters, condenser and pump majorly. The result of thermodynamic analysis is estimeted in terms of 42% of plant thermal efficiency, 70 % of steam generation unit efficiency (Economizer. Super heater), Maximum heat absorbed by economizer of plant as 39% is achieved, with 40TPH of coal consumption. Boiler, High Pressure Turbine, Intermediate Pressure Turbine, Super Heater have found best performance in analysis and Reheating-Regenerative rankine method improves 6-8% in thermal efficiency also. This analysis concluded that energy efficiency is greater than exergy efficiency which identifies the power plant utilities and further improvement for efficient power generation opportunities like waste heat recovery technology employment.*

***Keywords:** Energy-Exergy Analysis, Irreversibility Analysis, Reheating-Regeneration Rankine cycle.*

I. INTRODUCTION

The massive amount of heat is transferred between all utilities of thermal power plant and its significantly affect the plant performance. The 1st Law of Thermodynamic is quantitative assessment of work and heat and its interaction with equivalent forms of energy between system and surrounding. The degradation of high grade energy of plant is cause of thermal deficiency. The evaluation of real performance of thermal system and quality of energy are possible by the exergy estimation. The Exergy expresses the maximum achievable work from a system at a given state when interacting with environment. The energy-exergy analysis of combined reheating-regeneration rankine cycle have been investigated with major units ,like Boiler, LPT/IPT/HPT, Condenser, Feed pumps, Deaerator, etc.

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The main objective of energy-exergy modeling is to identify the losses and actual performance of components. The various researchers have been conducted on energy-exergy analysis of thermal systems, power plant components, and renewable energy conversion systems.The relations between the exergy and energy and its application of conventional and modern examples have been analyzed,
authors also examined exergy analysis of industrial process heating, steam power plant in several aspects of thermodynamic performance like energy and exergy efficiencies for different operating parameters such as boiler temperature and pressure, cycle work output, mass fraction ratio and irreversibility .Author also studied exergy analysis of SOFC-Trigeneration system, CHP-ORC and CCHP,CCPP system for its optimize design and economic-environmental performance[1-2,4-5,10,12,14-15,19].The EGM (entropy generation minimization) method concluded that whenever entropy production is minimized, useful energy is maximized[3].The exergy analysis of combustion chamber gives exergy destruction is 50% of overall exergy destruction of cycle, and effect of intermediate pressure-ratio and effect two stage of reheating on combined GT-ST power cycle performance by using 2nd law thermodynamic approach, and authors conducted a second law analysis for the performance evaluation of ejector-absorption cooling system and gas turbine cogeneration system with effect of tri-generation of energy [6,7,9.16-17].The concept of entropy generation and irreversibility of thermodynamic system identify the components having major exergy losses in steam power plant, Authors have been examined the maximum energy loss through condenser of solar thermal based steam power plant in another study[8,11,13].The parametric study through exergo-economic approach of 299 MW of combined power generation which utilize waste heat from a Gas Turbine-Modular Helium Reactor and runs two Organic Rankine Cycle (ORC). The operating parameters such as compressor pressure ratio, turbine inlet temperature, evaporator's temperature, pinch point temperature difference in the evaporators and degree of superheat at the ORC turbines inlet have been investigated. The results of analysis show the worst exergoeconomic performance of precooler, intercooler and ORC condensers [18].The review of 4-E (energy, exergy, exergonomic and economic) concept for different-different power generation techniques. Author addressed the boiler condenser and combustion chambers have major exergy destruction in case of rankine power cycle and gas-turbine power cycle respectively [20].

The analysis of ORC system for waste heat recovery purpose of wind, geothermal, hydroelectric alternative type energy conversion systems is discussed, another author reviewed the technical methods for performance assessment of energy and exergy analysis of different configurations of the Combined Cooling and Heating plant in term of heat recovery boilers. Energy-Exergy analysis of thermal systems provide the opportunity to improvement and identify the location of losses and losses mainly occurs during the operation and it remark as exergy destruction[21-22].

II. Brief of Reheating-Regeneration Rankine Power System

The proposed plant is integrated with three steam turbines, which are HPT.IPT and LPT with different operating conditions, one re-heater unit, one super heater, one economizer, five extractions have been combined with turbines (one with HPT, three with IPT, and another one is with LPT), Third extraction with IPT is works as deaerator unit. One condenser, one condenser pump and one boiler feed pump respectively.

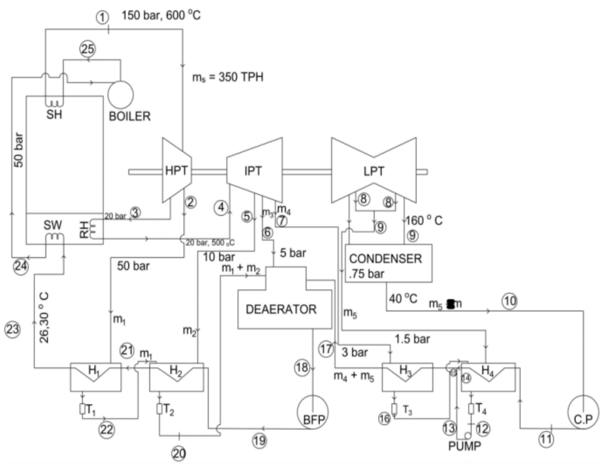

Figure 1: Plant Schematic of Combined Reheating Regenerative Rankine cycle

The all connection and locations of unit are shown in figure 1, and plant specifications have been provided in table-1

Table-1 Specifications of Combined Reheating Regenerative Rankine Plant-

Name of Unit/Parameters	**Specifications**	**Name of Unit/Parameters**	**Specifications**
Steam Flow Rate (ms)	350 TPH	Condenser pressure maintained	0.75 bar
HPT input	150 bar, 600^{0}c	Condenser input and output temperature	160 0C&40 0C
Reheater input	20 bar,500 0C	Heater3(extraction from IP)	3 bar
Heater1(extraction from HP)	50 bar	Heater4(extraction from LP)	1.5 bar
Heater2(extraction from IP)	10 bar	IPT input	20 bar ,500 0C
Deaerator(extraction from IP)	5 bar		

III. Thermodynamic Analysis of Combined Reheating-Regenerative Rankine Power Cycle

All equations of analysis are based on fundamental approach of 1st law and 2nd law of thermodynamics, and steam properties as well. A simplified mathematical model of basic thermodynamic approaches is used in analysis. Mass and energy balance equations has been applied in all thermal utilities. In order to simplify the analysis, some assumptions are generally made as follows and adopted from P K Nag Rankine Reheating-Regeneration model[23]:

1. The process is considering steady flow throughout working of system and thermal utilities also consider as a control volume (CV).
2. The mass flow at every point within the control volume does not vary with time. .
3. The efficiency of both turbines and pump assumed isentropic for analysis.
4. The thermodynamic equilibrium exits in all units at any given time.

Thermodynamic Analysis of Combined Reheating-Regeneration Rankine cycle

For evaluation of unknown value to enthalpy and entropy at condenser and pump is estimated as following energy equation as mentioned as per given pressure and temperature from steam table.

For x at condenser (400c, 0.075 bar)

Sg= Sf + xSfg (1)

Where Sfg= Sg - Sf (2)

Enthalpy at condenser inlet (H9),

Hg = Hf + xHfg (3)

Where Hfg = (Hg – Hf) (4)

Liquid Enthalpy of condensate after condensate pump (H11)

H11 = H10+ sp. Vol. * P (Sp Vol value taken from steam property) (5)

Energy Equation for all Feed water Heaters as followings

Total heat added to boiler equal to heat supplied by FWH through increasing temperature of water from CEP and FWP.

m1 (H2 – H22) =∑mΔH_FWH + (1 – m)∑ΔH_FWH (6)

(Assume same mass flow rate entering at the steam generator inlet from H.P turbine inlet)

Turbine work can be found by using following equations

Turbine Work- HPT Work = ms (H1 –H2) + (ms –m1) (H2 - H3) (7)

IPT Work = HPT Work + (ms –m1) (H4 –H5) + (ms –m1 – m2) (H5 –H6) + (ms –m1 –m2 –m3) (H6 – H7) + (ms –m1 –m2 –m3 –m4) (H7 –H8) (8)

LPT Work = HPT Work + LPT Work + (ms –m1 –m2 –m3 –m4 –m5) (H8 –H9) (9)

Heat Addition (Q1) to the plant through feed pumps,SuperHeaters and boiler are

Q1 = ms (H1 –H23) + (ms –m1) (H4 –H3) (10)

Heat of thermal utilities and its absorbance are given by the followings equation.

Coal consumption (m_coal)

m_coal* cv = Q1 (10a)

The reheating-regenerative rankine cycle efficiency estimated as follows

Reheating-Regenerative Efficiency of cycle=ηthermal_reh-reg = wnet/Q1 (11)

Rankine Thermal Efficiency = ηthermal_rankine = (h1-h8/h1-h23) (12)

Heat absorb by steam generator units like economizer,superheater,boiler and reheater following energy equation

Q_unit = mass of water through units × Δ H_unit / m_coal (13)

Percentage of heat absorbed by steam generator units = $\frac{\Delta H\_units}{H_1 - H_{12}}$ (14)

Efficiency of steam generation (ηsteam generator) = $\frac{m_s(H_1 - H_{23})}{m_c \times c.v}$ (15)

Condenser flow (condition for LPT)

= ms - $\sum_1^5$ m= ms- (m1+m2+m3+m4+m5) (16)

Water flow from Cooling Tower

ms(cpΔt + L.H)cond = mw(cpΔt)c.t side (17)

Exergy Equations for Plant utilities

Exergy (ϵ)output/input $= m \times c_p \times T_o \left[\frac{T_b}{T_o} - 1 - \ln\frac{T_b}{T_o}\right]$ (18)

Where Tb = Temperature of boiler and To = Ambient temperature

Loss of energy in boiler can be estimated by irreversibility in boiler

IRR_BOILER = To$\sum \Delta s$, where $\Delta s = c_p \ln(\Delta T_{out} | \Delta T_{in})$ (19)

Rate of exergy decrease = $\epsilon_{output} - \epsilon_{input}$ (20)

Rate of exergy loss during steam generation = $\frac{\epsilon_{in}}{\epsilon_{out}}$ (21)

EDD ratio = T0Δs/Qboiler (22)

Exergetic efficiency (ηEX_boiler) = 1- EDD (23)

Rate of exergy increase in steam = ms [H1-H23-T0(s1-s23)] (24)

(Similar exergy equations are applicable for turbines, heaters also).

IV. RESULTS AND DISCUSSION

Following results have been concluded in the present analysis are provide in table-2.

Table-2 Component Efficiencies (η_I & η_{II}) comparison of combined Reheating-Regenerative Rankine Thermal Power Plant

Component	First law efficiency (η_I)	Second law efficiency (η_{II})
Boiler	86.80%	64.90%
High pressure turbine (HPT)	86.25%	79.39%
Intermediate pressure turbine (IPT)	96.40%	87.20%
Low pressure turbine (LPT)	97.67%	46.45%
Super heater	92.39%	52.50%
Condenser	89.77%	67.47%

The comparative results and observations of 1st&2nd law efficiency and exergetic performance of proposed plant have been provided in Table 2 and 3 respectively.There are various resultant graphs also drawn for performance evaluation as Exergy destruction, Percentage Heat Absorbed and Rate of Heat loss, Plant components efficiencies etc.

The variation in heat absorbs by components of steam generation unit of plant is shown in figure 2. More than 35% of heat is absorbed by the economiser as compare to other components.

Table-3 Exergy Observation of components of combined Reheating-Regenerative Rankine Thermal Power Plant

Components	Exergy (?)??????/?????? = ?? × ?? × ?? ??/?? - ?? - ???/??		?? = ?????	IRR = To ??	Rate of exergy decrease = ?????? ??????	Rate of exergy loss = ??/???	EDD ratio = IRR/Qin (Qin means Qboiler)
	? output (MW)	? in (MW)	(kj/kg k)	(kj/kg)	MW		
Boiler	25.13	21.28	0.125	37.25	3.85	0.846	0.014
Reheater	30.4	15.66	0.487	145.3	14.74	0.515	0.054
Super Heater	49	25.13	0.517	154.3	23.97	0.512	0.057
Economiser	21.28	12.07	0.327	97.7	9.21	0.571	0.036
HPT	29.861	49.589	0.411	122.47	19.72	0.60	0.045
IPT	7.622	30.986	0.874	260.45	23.32	0.246	0.097
LPT	2.557	8.666	0.557	165.98	6.11	0.290	0.061
Condenser	0.048	2.157	0.6477	193.0146	2.109	44.6	08.98
Heater1	1.9	1.083	0.606	180.5	0.817	0.98	.006
Heater2	0.004	0.00311	0.315	93.8	0.0009	0.77	0.034
Heater 3	0.071	0.045	0.250	74.5	.026	0.63	0.027
Heater 4	0.076	0.0077	0.559	166.58	0.068	0.10	0.058
Dearator	1.105	0.813	0.207	61.66	0.292	0.73	0.022

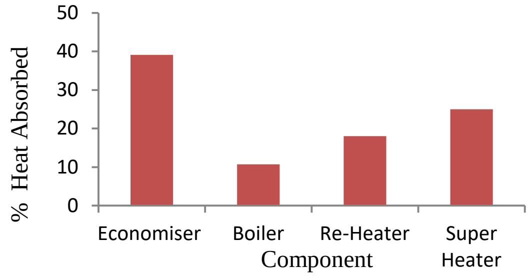

Figure 2: Components Heat Absorbed of Combined Reheating Regenerative Rankine cycle

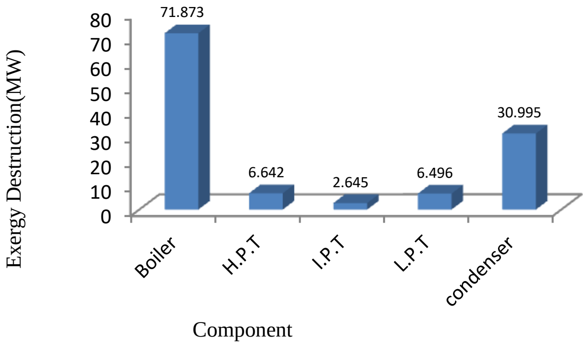

Figure 3: Exergy Destruction in components of Combined Reheating Regenerative Rankine cycle

Exergy destruction of boiler is maximum with respect to condenser and turbine respectively which is clearly shown in figure 3.The rate of exergy losses have been estimated of different components of plant.The 60% to 77% of exergy losses founded in high pressure turbine ,Heater 12,3 and deaerator which is shown in figure 4. On comparing figures 3 & 4, the Boiler, turbine (HPT), heaters and dearator are to be redesigned due to major exergy loss.

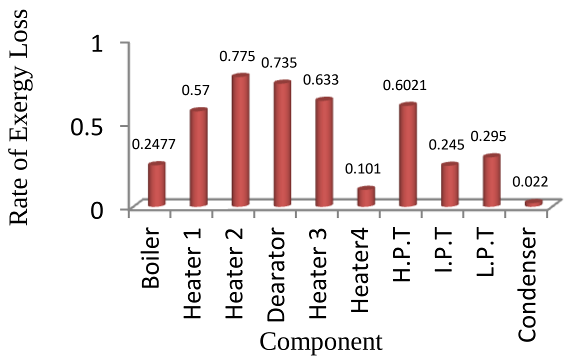

Figure 4: Exergy Loss in components of Combined Reheating Regenerative Rankine cycle

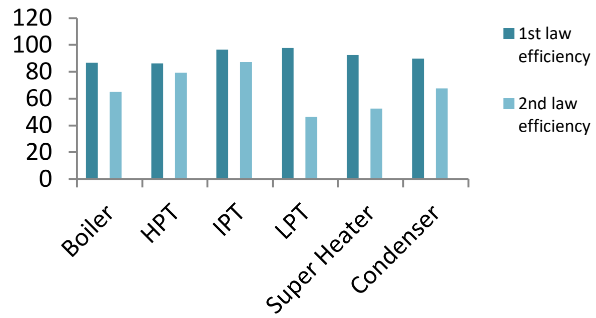

Figure 5: 1st law and 2nd law efficiency of Combined Reheating Regenerative Rankine cycle plant components

The efficiencies comparison between plant components is clearly shown in figure 5, the low pressure turbine has considerable gap between 1st and 2nd law efficiencies. So there is an opportunity of improving low pressure turbine efficiency by decreasing irreversibilities.

V. CONCLUSIONS

Complete thermodynamic study of proposed reheating-regenerative plant was done. In this analysis 1st law efficiency, 2nd law efficiency, quality of steam, coal consumption, inlet and outlet temperatures, pressure, exergy, mass flow rate, exergy destruction of each components have been estimated. It was found that exergy destruction of boiler is always greater than condenser due to the high grade energy utilization and more irreversibilities. The decrease in rate of exergy was found at turbine extractions like heaters and deaerator of plant. The steam quality was found about 89-90% and coal consumption is 40TPH estimated with the steam flow rate of 350 TPH. Steam generator and plant efficiency have been analyzed 70% and 42% respectively. It is concluded that major portion of steam lost is due to steam generator, turbines and heaters of a power plant. However, boiler, HPT, IPT and super heater are found in best performance in our analysis. The opportunities of Reheating-Regeneration for proposed steam power plant helps to improve thermal efficiencies of steam power cycle and which is gained by 6-8%.

VI. NOMENCLATURE AND ABBREVIATIONS

TPH=Ton per hours
MW=MegaWatt
HPT=High Pressure Turbine
LPT=Low pressure Turbine
IPT=Intermediate Pressure turbine
EGM=Entropy Generation Minimization
GT-ST=Gas Turbine-Steam Turbine
CHP=Combined Heating and Power
CCHP=Combined cooling heating and power
ORC=Organic rankine cycle
CCPP=Combined cycle power plant
SOFC=Solid oxide fuel cell
HRSG=Heat recovery steam generator
GAX=Generator absorber heat exchanger
cv= Calorific value
RH=Re-Heater
SH=Super Heater
LH=Latent Heat
EDD=Exergy Destruction

Q_{ECO}=Heat generated by economizer
S_g=Vapor entropy
S_f=Liquid entropy
S_{fg}=Liquid-Vapor entropy
h_g= Vapor enthalpy
h_f=Liquid enthalpy
h_{fg}=Liquid-Vapor enthalpy
η_{th}=Thermal Efficiency of plant
ε= Exergy
I_{RR}=Irreversibility
η_{EX}=Exergetic Efficiency
mfr= Mass flow rate of steam

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