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Investigating the Effects of Parametric Variation over Performance of Boiler-Turbine Cycle

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Abstract: In this paper, the effects of variation in ambient temperature, flue gas temperature and condenser pressure over performance of boiler and turbine cycle is presented. The study is carried out with EES software. The change in ambient temperature is seriously deteriorating the boiler exergetic performance as its exergy efficiency reduces by 2.5% with increase in environmental temperature from 27℃ to 45℃ while the boiler total energy loss reduces almost 1% for same increase in ambient temperature. The turbine second law efficiency is affected slightly by ambient temperature. Increase in temperature of exhaust flue gas has adverse effect over boiler energy efficiency, which reduces by almost 1% with flue gas temperature variation from 110℃ to 130℃. The increase in condenser pressure is reducing the turbine energy efficiency to more than 3% with variation from 0.05bar to 0.3bar. Condenser exergy efficiency is decreasing sharply with increase in its pressure. The effect of variation in condenser pressure over net output of the boiler-turbine cycle has also been studied and it is found to be decreasing with increase in condenser pressure.
Keyword: Ambient temperature, Boiler-turbine cycle, Condenser pressure, Flue gas, Plant performance.

I. INTRODUCTION

Owners are increasingly demanding the plant with guaranteed performance. This has put the tremendous pressure over designers to analyze the thermodynamic performance of various componenets of the plant under varying operating condition with high degree of accuracy. This requires the use of some advanced tool of thermodynamic performance assesment like exergy analysis and simulation software, which can accurately calculate the effect of variation in parameters such as ambient temperature, flue gas temperature, excess air, gain in condenser cooling water temperature, feed water inlet temperature to boiler etc. The conventional first law anlysis evaluates the efficiency with which the energy conversion takes place while the exergy (also termed as availability/available energy) analysis, which is based on the first and second law together, provides a tool to clearly identify the internal irreversibility in the process and energy lost to the environment. In the series of work done in the field, Salari Mehdi and Amir Vosough [1] analyzed the effects of variation in ambient temperature over first and second law efficiencies of the plant. They also found that the highest exergy loss take place in the boiler when overall plant is considered and within the boiler combustion process was major contributor for exergy destruction. Marc A. Rosen and Raymond Tang [2] also examine the effect of decreasing excess air fraction and/or the stack gas temperature. The result shows an increase of 1.4% in overall plant energy and exergy efficiency with the decrease in fraction of excess air from 0.4 to 0.15 and both the efficiencies increases by 3.5% with decrease in exhaust flue gas temperature by 62°C (i.e. from 149 to 87°C). Further, they observed the 4.7% increase in both the efficiencies when the theoretical combustion air is used and stack gas temperature is 87°C. In a thermodynamic analysis of a 62.5MW coal based thermal power plant on a case study approach, Suresh M. V. J. J et al. [3] presented the variation of plant energy and exergy efficiency with respect to change in value of parameters such as cooling water temperature gain across the condenser, inlet air temperature, excess air, condenser pressure and power output.

Ebrahim Hajidavalloo and Amir Vosough [4] use the exergy analysis to investigate the irreversibility rate of main components of a super critical power plant at different ambient temperature. They modeled the condenser behavior by following two different approaches namely constant condenser pressure and variable condenser pressure. A considerable difference in the results of two different approaches was observed, but they recommend the variable condenser pressure approach for exergy analysis as it is close to the actual condition. In a thermodynamic modeling and optimization of a dual pressure reheat combined power cycle T. Srinivas [5] optimized the combined cycle system at a gas inlet temperature of 1400°C with the modern gas turbine blade cooling system. After validation of simulated model of the present double pressure reheat heat recovery steam generator model they compared the exergetic losses in combined cycle system with the plant and published data.

In a thermodynamic analysis of a 315MW super critical steam power plant, F. Ahmadi Boyaghchi [6] calulated the plant performance in terms of energy and exergy efficiencies, energy loss rate, exergy destruction rate, improvement potential rate etc. He also performed a parametric study to investigate the effects of high-pressure turbine inlet pressure, temperature, mass flow rate and reheat pressure, temperature, mass flow rate over plant efficiencies and exergy destruction of the plant components. Study concluded that the maximum energy loss of 38.4% of the input takes place in condenser and maximum exergy destruction of 35.2% occurs in boiler. Cycle performance improves when high-pressure turbine inlet pressure, temperature and intermediate pressure turbine inlet temperature increases. The optimum pressure value is obtained as 46bar and flow rate of 240kg/s to the inlet pressure turbine is found as the value for maximum plant performance. Chao Fu et al. [7] in a paper presented a systematic study on coal to power processes with respect to thermodynamic, technological and economic factors. Unlike the traditional exergy analysis which focuses on irreversibility in existing processes, a new methodology is adopted to investigate the thermal efficiency from its theoretical maximum to practical values by adding irreversibility one by one. Various measures for increasing the thermal efficiency by 0.1% points are also presented. M. M. Rashidi et al.[8], in an exergy analysis to guide the improvement of a steam cycle with two reheater, three stage turbine and six points of extraction, investigated the effects of turbine inlet pressure, boiler exit steam temperature and condenser pressure on the first and second law efficiencies. In an another study by A. Sivakumar [9], the percentage of excess air was varied from 10% to 31% and found that the efficiency of boiler increased with the passage of excess air up to an extent and boiler showed a high percentage of 82.02% with the passage of 28% of excess air. M. Yunus et al. [10] conducted a second law based detailed parametric study of a thermal power plant, by considering the effects of various parameters such as reference air temperature, condenser pressure, increase in condensere cooling water temperature, steam temperature etc.. In a thermodynamic analysis of a 32MW coal fired thermal power plant, P. Regulagadda et al.[11] determined the plant performance under various operating conditions including different reference temperature, steam flow, pressure and temperature. In a parametric study of a boiler of gas fired steam power plant, S. Arefdehgani and O. K. Sadaghiyani [12] concluded that when stack gas temperature decreases from 159 to 97°C the energy and exergy efficiency increases nearly 2.196% and by decreasing excess air fraction from 0.4 to 0.15 the two efficiency of the plant increases by 0.497% and 0.46% respectively. In an exergy analysis, L. Patttanayak [13] evaluated the performance of a 500MW coal fired boiler by varying the excess air and concluded that with 0.5% increase in excess O_2% caused 0.65% decrease in combustion exergy efficiency and 0.47% boiler exergy efficiency. In another boiler parametric study, M. Bakhshesh and A. Vosough [14] found that the performance of a power plant with a gas fired steam generator improves with the decrease in stack gas temperature and excess air quantity. Gholam Reja Ahmadi and Davood Toghraie [15] in an energy and exergy analysis of a steam cycle determined the effect of changes in main steam temperature and pressure; reheat steam temperature and pressure; mass of steam extraction and condenser pressure upon unit load of high pressure and intermediate pressure turbine and condenser. Authors [16-20] have studied the effect of ambient temperature and condenser pressure upon performance of the steam generator and power plant. Harshal D. Akolekar et al. [21], in addition to optimize reheat and regenerative cycle process parameters such as reheat pressure, extraction pressure of bled steam and mass fraction of bled steam compares the efficiencies of eight kinds of steam power cycles made for different boiler pressures and turbine inlet steam temperatures. Marc A. Rosen and Raymond Tang [22], in their study using energy and exergy analysis investigated the effect of increasing reheat pressure and found that the irreversibility rate with heat transfer in boiler decreases with increase in reheat pressure, but the overall plant exergy efficiency decreased due to relatively large decrease in turbine output.

The studies carried out so far in the field were focussed either upon plant performance or only to the boiler but in the present paper effect of variation in some important parameters over performance of boiler-turbine cycle and condenser have been analyzed.

II. METHODOLOGY

In this paper, the effects of variation in some parameters have been evaluated in terms of energy and exergy efficiency and net work done. The pioneers of the field [23-28] have described the basic concepts of exergy analysis and its procedure. The basic equations of mass, energy and exergy balances for a control volume at steady state by considering the changes in potential and kinetic energy as negligible can be written as [29]:

$\Sigma\, m_i = \Sigma\, m_e$

$Q + \Sigma\, m_i h_i = \Sigma\, m_e h_e + W$

$\Sigma\,(1 - T_0 / T)\, Q + \Sigma m\, \varepsilon_{in} = \psi_w + \Sigma m\, \varepsilon_{out} + I_{destroyed}$ Where $I_{destroyed}$ is exergy destroyed

and $I_{destroyed} = T_0\, \Delta S$ or $T_0\, (S_{gen})$

Also total exergy, $\psi = m\,\varepsilon = m\,[(h - h_0) - T_0\,(s - s_0)]$

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In the above equations ε_{in} is the specific exergy associated with mass inflow and ε_{out} is the specific exergy associated with the mass outflows, ψ_w is useful workdone on/by system.

The energy or first law efficiency and exergy or second law efficiency for the component are defined as:

η_I = Products energy /Total energy input

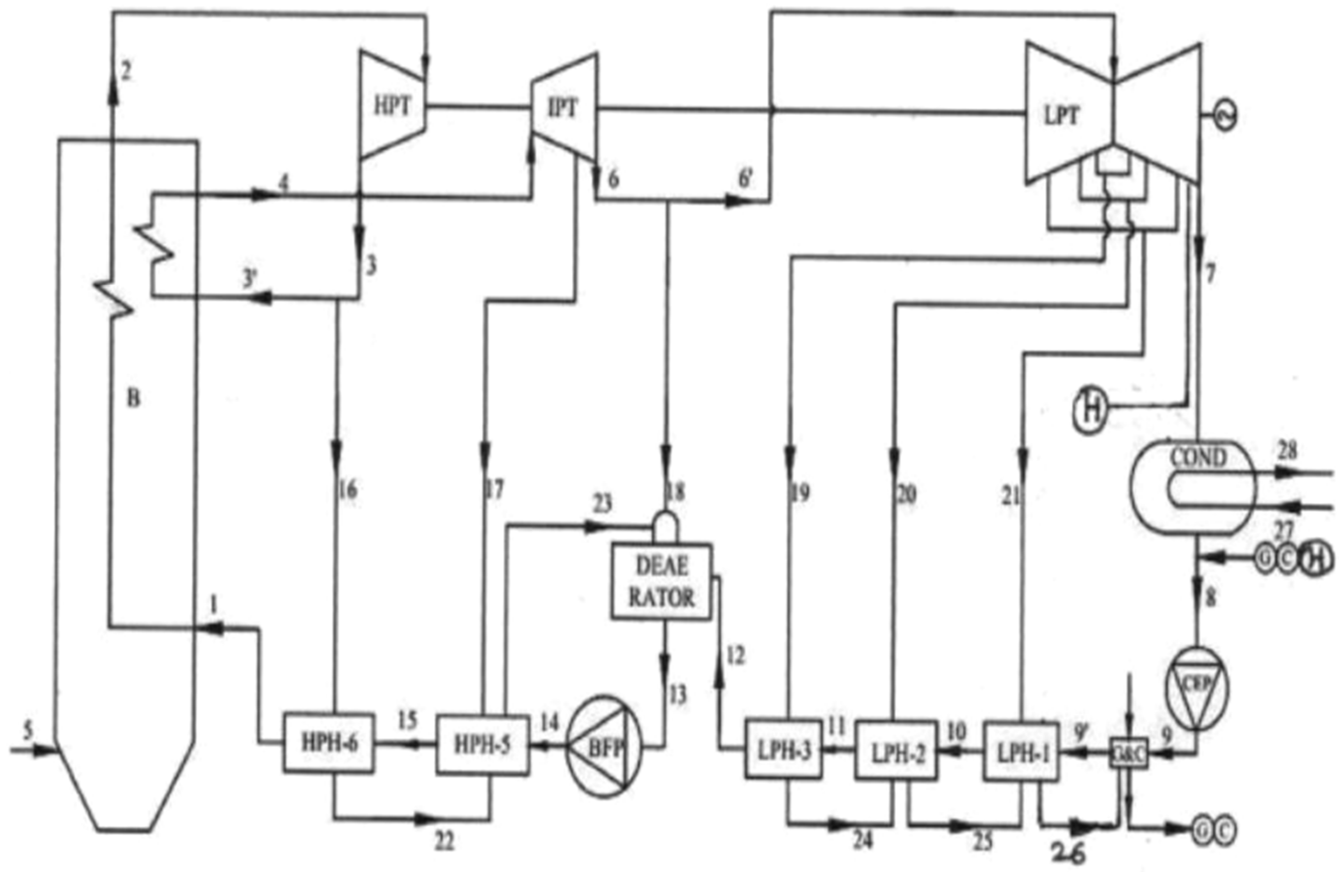
η_{II} = Products exergy /Total exergy input

Based on the components for which the above equations are employed the definition of product is decided (for instance, the heating of feed water, or generation of steam, the power in a turbine) and the input (the amount of energy or exergy spent to obtain the product). In some systems, there is no universal agreement as to what are an input and an output. Therefore, their efficiency must be defined by the expression,

Efficiency = Energy or exergy out/Energy or exergy in

III. PLANT DETAILS

Schematic diagram (Fig. 1) and operating data collected form main control room of the plant and given in author's earlier paper [30] are used.



B – Boiler LPH – Low Pressure Heater
HPT – High Pressure Turbine HPH – High Pressure Heater
IPT – Intermediate Pressure Turbine CEP – Condensate Extraction Pump
LPT – Low Pressure Turbine BFP – Boiler Feed Pump
G and C – Gland Steam Condenser and Drain Cooler COND– Condenser
H – Condensed steam from LPT

Fig. 1. Schematic diagram of 250MW thermal power plant [30]

IV. ENERGY AND EXERGY BALANCE EQUATIONS

According to general equations given under methodology, section wise energy and exergy equations are as given below:

A. Steam Generator or Boiler

Main function of boiler is to generate the steam by transferring the energy of fuel to feed water. Thus, expressions for boiler energy efficiency ($\eta_{I\ boiler}$) and exergy efficiency ($\eta_{II\ boiler}$) can be written as:

$\eta_{I\ boiler}$ = Energy gain by (feed water + reheat steam)/
Energy supplied by fuel

or $\eta_{I\ boiler} = (E_{out})_{net} / (E_{in})_{net}$

and $\eta_{IIboiler}$ = Exergy gain by (feed water + reheat steam)/Exergy supplied by fuel

or $\eta_{II\ boiler} = (\psi_{out})_{net} / (\psi_{in})_{net}$

With reference to the schematic layout (Fig. 2) of steam generator section of the considered plant:

$(E_{in})_{net} = m_5 h_5 = m_f \times C.\ V.$

$(E_{out})_{net} = (m_2 h_2 - m_1 h_1) + m_{3'} (h_4 - h_{3'})$

$\psi_{in} = m_5 \text{ x } \gamma \text{ x LHV}$

Where γ is specific exergy factor and LHV is lower heating value of coal.

$\psi_{out} = E_{out} - T_0[(m_2 s_2 - m_1 s_1) + m_{3'}(s_4 - s_3)]$

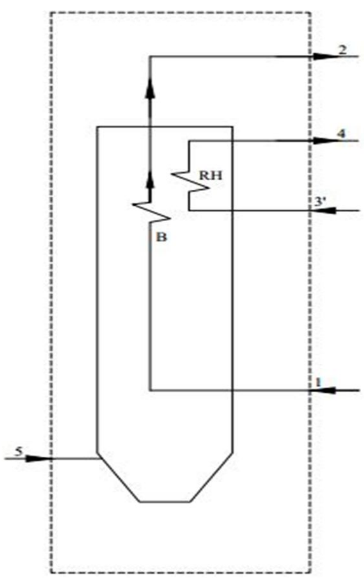


Fig. 2. Boiler

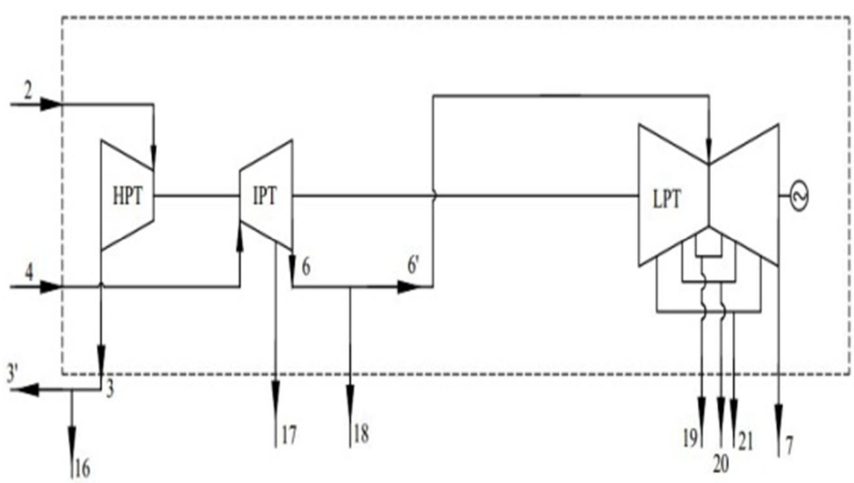


Fig. 3. Turbine section

B. Turbines

Turbines are used to convert the thermal energy of steam into mechanical work. Thus, turbines are analyzed as thermodynamic systems producing mechanical work by using thermal energy of steam and expressions for turbine energy efficiency ($\eta_{I\ turbine}$) and exergy efficiency ($\eta_{II\ turbine}$) can be written as:

$\eta_{I\ turbine}$ = Net workdone by the turbine/Net energy input to the turbine = $(W_T)_{net} / (E_{in})_{net} = (E_{out})_{net} / (E_{in})_{net}$

$\eta_{II\ turbine}$ = Net workdone by the turbine/Net exergy input to the turbine = $(W_T)_{net} / (\psi_{in})_{net}$

With reference to the schematic layout of turbine section (Fig. 3):

$$(E_{in})_{net} = m_2(h_2 - h_{3t}) + m_4 (h_4 - h_{17t}) + (m_4 - m_{17}) (h_{17t} - h_{6t}) + m_{6'}(h_{6'} - h_{19t}) + (m_{6'} - m_{19}) (h_{19t} - h_{20t}) + (m_{6'} - m_{19} - m_{20}) (h_{20t} - h_{21t}) + (m_{6'} - m_{19} - m_{20} - m_{21}) (h_{21t} - h_{7t})]$$

$$(\psi_{in})_{net} = (E_{in})_{net} + m_2 T_0 (s_3 - s_2) + T_0 [m_4 (s_{17} - s_4) + (m_4 - m_{17}) (s_6 - s_{17})] + m_{6'} T_0(s_{19} - s_{6'}) + (m_{6'} - m_{19}) T_0 (s_{20} - s_{19}) + (m_{6'} - m_{19} - m_{20}) T_0 (s_{21} - s_{20}) + (m_{6'} - m_{19} - m_{20} - m_{21}) T_0 (s_7 - s_{21})]$$

$$(E_{out})_{net} = m_2(h_2 - h_3) + m_4 (h_4 - h_{17}) + (m_4 - m_{17}) (h_{17} - h_6) + m_{6'}(h_{6'} - h_{19}) + (m_{6'} - m_{19}) (h_{19} - h_{20}) + (m_{6'} - m_{19} - m_{20}) (h_{20} - h_{21}) + (m_{6'} - m_{19} - m_{20} - m_{21}) (h_{21} - h_7)$$

$(W_T)_{net} = (E_{out})_{net} = (\psi_{out})_{net}$

C. *Condenser*

The condenser acts as a heat exchanger and transfers the heat of the turbine exhaust steam to the cooling water. Therefore, expressions for condenser energy efficiency ($\eta_{I\ cond}$) and exergy efficiency ($\eta_{II\ cond}$) can be written as:

$\eta_{I\ cond}$ = Increase in energy of the condenser cooling water / Decrease in energy of the turbine exhaust steam

or $\eta_{I\ cond} = (\Delta E)_c / (\Delta E)_h$

and $\eta_{II\ cond}$ = Increase in exergy of the condenser cooling water/ Decrease in exergy of the turbine exhaust steam

or $\eta_{II\ cond} = (\Delta\psi)_c / (\Delta\psi)_h$

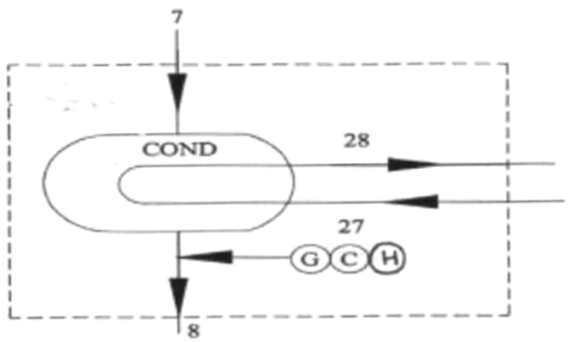


Fig. 4. Condenser

With reference to the schematic layout of condenser section (Fig. 4):

$(\Delta E)_c = [m_{27}(h_{28} - h_{27})]$

$(\Delta E)_h = [m_7(h_7 - h_8) + m_{26}(h_{26} - h_8)]$

$(\Delta\psi)_c = m_{27}[(h_{28} - h_{27}) - T_0(s_{28} - s_{27})]$

$(\Delta\psi)_h = m_7[(h_7 - h_8) - T_0(s_7 - s_8)] + m_{26}[(h_{26} - h_8) - T_0(s_{26} - s_8)]$

D. *Efficiency of Boiler-turbine Cycle*

$$\text{Energy efficiency of boiler-turbine cycle, \%} = \frac{\text{Total output of the boiler-turbine cycle}}{\text{Mass flow rate of the fuel} \times \text{higher calorific value of the fuel}} \times 100$$

$$\text{Exergy efficiency of boiler-turbine cycle, \%} = \frac{\text{Total output of the boiler-turbine cycle}}{\text{Exergy input to cycle}} \times 100$$

Table 1: Data of power plant at 250MW [30]

Stream	Physical State	Temp. t (°C)	Pressure p (bar)	Flow rate m (kg/s)	Sp. enthalpy h_t/ h (kJ/kg)	Sp. entropy s(kJ/kg K)
1	Water	255.00	167.78	204.79	1077.20/1067	2.7761
2	Steam	537.00	143.75	204.79	3426.24	6.49
3	Steam	347.20	40.05	204.79	3052/3088.43	6.56
3'	Steam	347.20	40.05	183.24	3052/3088.43	6.58
4	Steam	537.00	36.04	183.24	3534.66	7.25
5	Coal	85.00	1.03	47.05	13800	0.70
6	Steam	302.80	6.81	172.47	3030/3065.40	7.282
6'	Steam	302.80	6.81	161.74	3065.40	7.31
7	Steam	46.30	0.106	141.33	2410.72/2428	7.624
8	Water	46.30	0.106	162.78	193.81	0.656
9	Water	46.50	19.66	162.78	209.71	0.6575
9'	Water	50.10	19.66	162.78	210.56	0.706
10	Water	73.50	19.66	162.78	308.93	0.997
11	Water	92.70	19.66	162.78	388.00	1.222
12	Water	119.80	19.66	162.78	502.85	1.528

13	Water	158.30	6.108	204.79	663.00	1.923
14	Water	161.40	185.56	204.79	693.45	1.957
15	Water	197.70	185.56	204.79	848.92	2.311
16	Steam	347.20	40.05	20.10	3088.43	6.56
17	Steam	417.10	15.99	11.20	3278/3291.87	7.26
18	Steam	302.50	6.80	10.72	3030/3065.40	7.285
19	Steam	188.10	2.35	7.66	2790/2854.00	7.39
20	Steam	104.70	0.89	5.31	2640/2686.15	7.4
21	Steam	78.40	0.44	6.97	2511/2583.60	7.595
22	Water	202.50	39.81	20.10	864.40	2.35
23	Water	166.30	15.78	31.31	703.25	2.013
24	Water	97.70	2.12	7.66	409.39	1.282
25	Water	78.40	0.73	13.524	328.60	1.055
26	Water	76.4	0.41	19.93	220.1	0.73
G	Water	52.2	0.39	19.93	218.1	0.997
C	Water	99.7	0.27	0.107	417.76	0.706
27	Water	34.00	2.02	8750	142.32	0.491
28	Water	42.20	1.49	8750	176.65	0.6

* h_t – theoretical value

V. RESULTS AND DISCUSSION

The study is carried out with the help of EES (Engineering Equation Solver) software and results of varying ambient temperature, flue gas temperature and condenser pressure are shown in graphical form in Fig. 5 to 11.

A. *Effects of Change in Ambient Temperature*

Effects of change in ambient temperature over boiler energy and exergy efficiency is shown in Fig. 5. Boiler total heat loss decreases by almost 1% when ambient temperature increases from 27°C to 45°C. With the decrease in losses in boiler its energy efficiency will increase to the same amount. The possible reasons for improvement are decrease in losses due to exhaust flue gas, hydrogen and moisture in fuel, and the reduction in amount of heat required to preheat the combustion air or the increase in average temperature of heat addition if same amount of heat is used for preheating. As shown in Fig.6 the boiler exergy efficiency is decreasing with increase in ambient temperature possibly because of increased irreversibility in boiler. Further, a gradual slight reduction in turbine exergy efficiency (Fig. 7) is observed with the increase in ambient temperature.

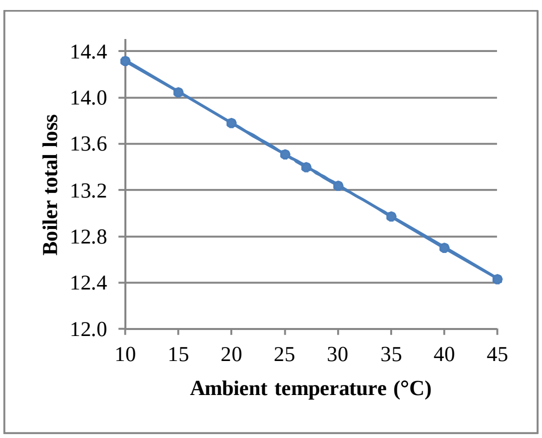


Fig. 5. Ambient temperature *vs* boiler total loss

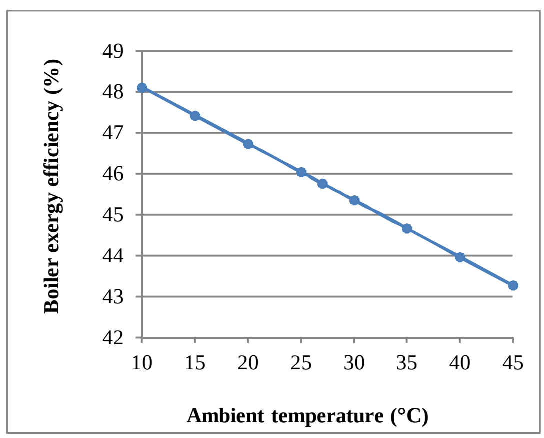


Fig. 6. Ambient temperature *vs* boiler exergy efficiency

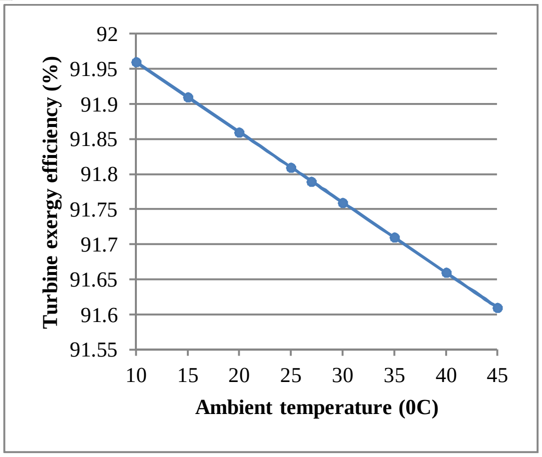


Fig. 7. Ambient temperature *vs* turbine exergy efficiency

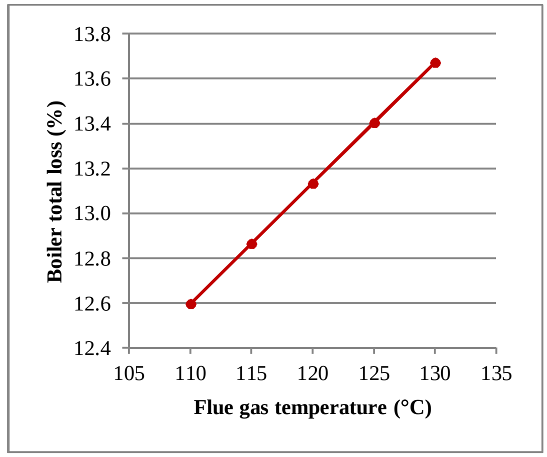


Fig. 8. Flue gas temperature *vs* boiler total losses

B. Effects of Change in Dry Flue Gas Temperature

Increase in temperature of the exhaust flue gas increases the boiler total loss as shown in the Fig. 8. With the increase of dry flue gas temperature by 20°C i. e. from 110°C to 130°C the total boiler loss increases over 1%.

C. Effects of Change in Condenser Pressure

Effects of change in condenser pressure over net work output of boiler-turbine cycle is shown in Fig. 9. Output of the cycle decreases significantly to the tune of almost 10MW with increase in condenser pressure from 0.05bar to 0.3bar while energy efficiency of turbine (Fig. 10) is decreasing considerably to the extent of more than 3.5% for the change in condenser pressure between same limit .The exergy efficiency of condenser (Fig. 11) is seriously affected with increase in its pressure but it may not be of great significance as the amount of exergy lost in condenser is very less in comparison to that occurs in boiler and turbine.

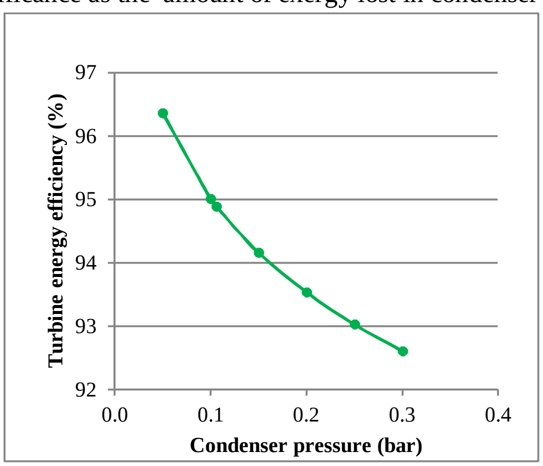


Fig. 9. Condenser pressure *vs* W_{net} (Boiler-Turbine cycle)

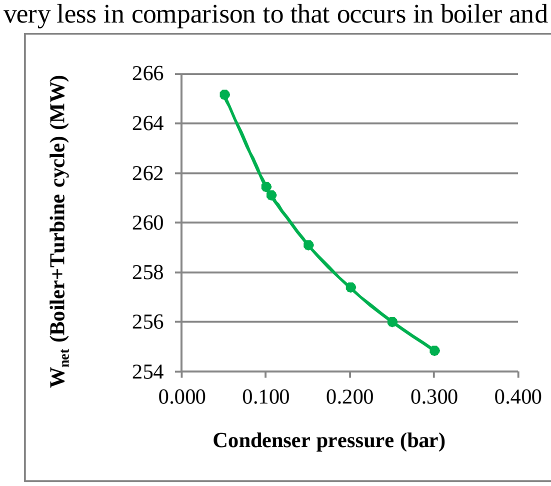


Fig. 10. Condenser pressure *vs* turbine energy efficiency

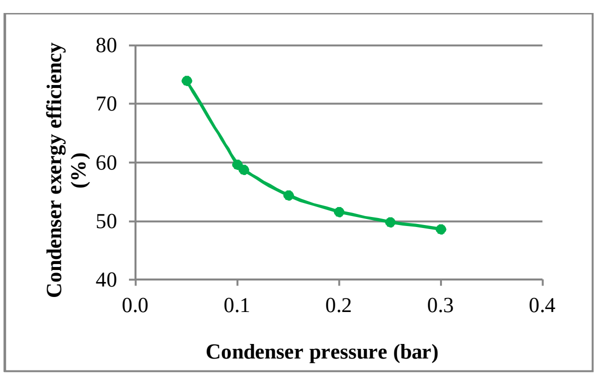


Fig. 11. Condenser pressure *vs* condenser exergy efficiency

VI. CONCLUSIONS

Based on the outcome of the investigation it can be concluded the increase in ambient temperature increases the boiler energy efficiency but also increases the irreversibility. The variation in ambient temperature is less influencing to the turbine performance. Increase in exhaust flue gas temperature reduces the boiler energy efficiency. Variation in condenser pressure is having more significant effect over the many performance parameter of boiler-turbine cycle. The net output of the cycle reduces moderately while the turbine energy efficiency and condenser exergy efficiency are affected considerably with increase in condenser pressure. As the plant personnel has no control over environmental temperature and also it has mixed type of affects over performance of plant components variation in its value may not be the matter of great concern but the fact is not same with the condenser pressure. So an important conclusion of the study is that the condenser pressure is an important influencing process parameter and it should not be allowed to increase for better performance of the plant.

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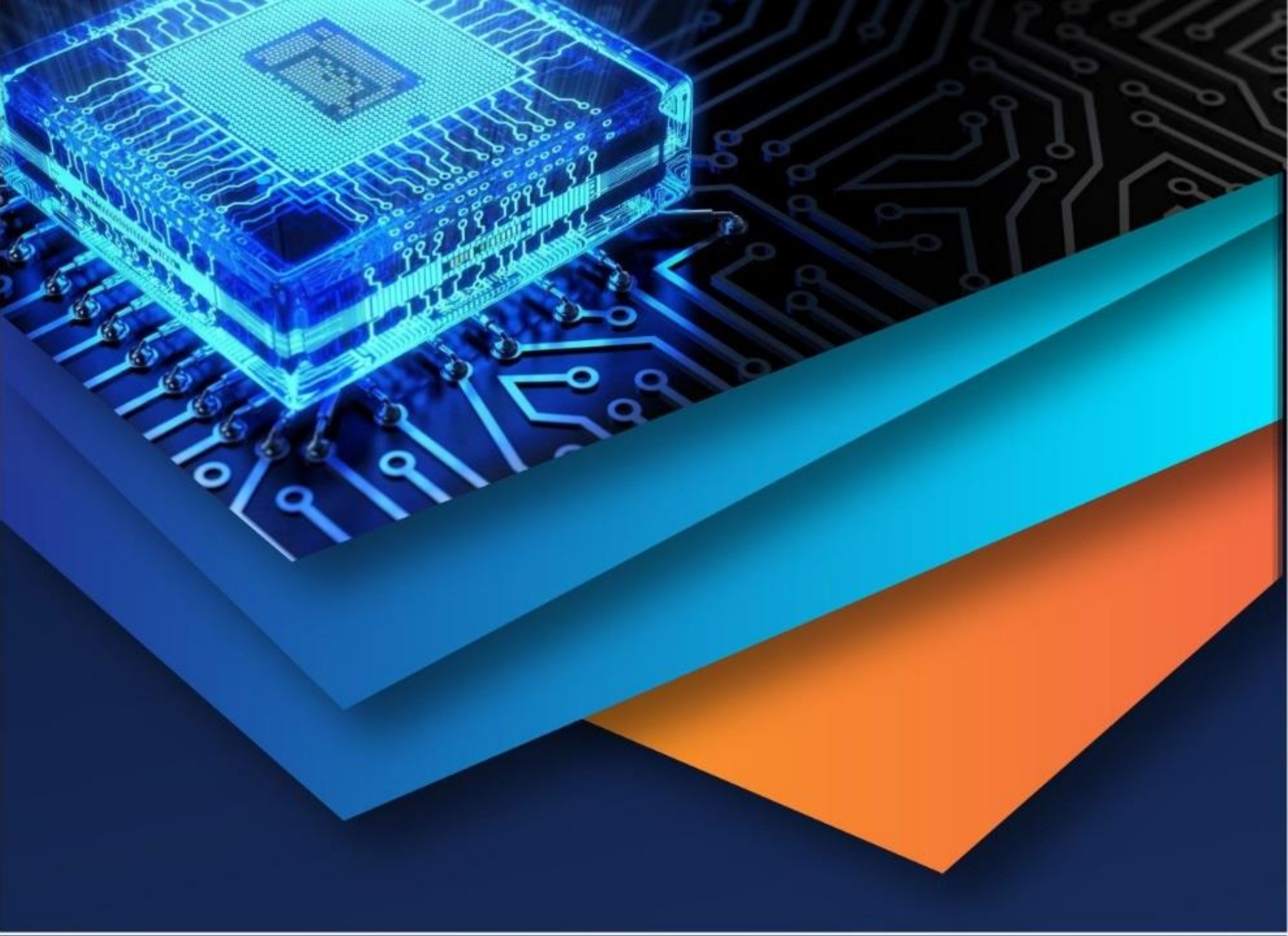

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