Energy and Exergy Investigation of a Thermal Power Plant Boiler

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Abstract

This investigative research work utilizes the fundamental concepts of energy and exergy principle to proportionate the energetic and exergetic performance of a gas fired steam power plant boiler in Bangladesh. The installed capacity of the power plant is 210 MW and comprises two-generation unit. The energy and exergy flow in the boiler have been considered in this study. Boiler energy and exergy efficiency have been analyzed as well as total irreversibility in the boiler also determined at different load conditions. Energy efficiency of the boiler is varied from 75% to 80% at different load condition where exergy efficiency is found to be changed from 41.4% to 43% at various load condition. The results from irreversibility analysis show that, exergy destruction increases with the increase of load and maximum for maximum load condition.

Keywords: *Power plant, energy flow, exergy, exergy destruction and exergy efficiency*

I. Introduction

Despite the global economic recession, Bangladesh, the country with huge prospects, maintains its sustained GDP growth rate more than 7%. The country needs high electricity growth to meet increased demand in order to supplement national economic growth, as sustainable, social and economic development depends on a country's sufficient power generation. Currently, about 90% of the people have access to electricity and per capita (including captive power) generation in Bangladesh is only 382 kWh. Including captive power and Renewable energy plant, total designed capacity is 20,775 MW [1]. The primary source of fuel is natural gas, which is about 53.9% of total installed capacity in Bangladesh. The government has therefore set a goal to provide everyone with electricity by 2021 and to ensure a reliable and quality electricity supply at a reasonable and affordable price. Majority of the power plant in Bangladesh of steam power plant type, it is essential to operate rigorous investigation to maximize the cycle performance of the power station. The most common method to investigate the performance of power plant is the application of conservation of energy principle. It gives indication about the quantity of energy transforming or processing. However, sometimes the term energy efficiency create misleading information about a system. The problem associated with energy analysis can be redeemed by introducing second law of thermodynamics, which asses the energy quality and introduce new terminology Exergy. In particular, it deals with energy degradation throughout a process, generation of entropy and irreversibility; and it affords ample potential to improve [3]. Irreversibility assessment is considered as a very useful method for optimizing complex thermodynamic technologies.

Many researchers have examined Exergy for various thermal power plants across the world. Rosen [6] assessed the overall performance of coal and nuclear power stations through exergy method. Habib and Zubair [7] carried out a second law investigation in a regenerative Rankine cycle power plants combined with reheating process. Vosoogh [8] conducted an energy and exergy investigation on a steam power plant boiler and reported that the decrease in excess air from combustion at a fraction of 0.4 to 0.15 will increase energy efficiency and exergy efficiency by 0.19 % and 0.37 % respectively. The author also suggested that, the above-mentioned efficiencies increase to 0.84 % and 2.3 % by reducing the smoke temperature from 137 °C to 90 °C. In terms of developing an optimization strategy, Kabiri et al. [9] examined the energy and exergy of a heat recovery steam generator system in a combined -cycle power plants. Wang et al. [10] analysed exergoeconomic assessment of a coal-fired ultra-supercritical thermal power station in China with the aim of understanding the cost - forming process and evaluating the economic conditions of all subsystems of the plant using SPECO (specific cost of exergy) technique. Medelin et al. [11] submitted an analysis and remodel of power plants providing a coupled analysis of pinch and exergy. This evaluation assesses the total, preventable and inevitable loss of exergy of the system that demonstrates the room for improvement of the equipment. Mousafarash and Ameri [12] addressed the energy, and exergy parameters of the Montazer Ghaem gas turbine power plant in the vicinity of Tehran, in order to evaluate the fuel costs of each component. The findings showed that in the combustion zone, the biggest expense of exergy destruction occurs. The combined cycle and Rankine cycle power plants were tested by Kaushik et al. [13] with energy and exergy analysis. This article provides information that the condenser contained the greatest exergy loss and therefore the greatest exergy defect was due to the inadequacy of reasonable combustion and ventilation.

Reddy and Alaefour [15] showed interesting data in the assessment of exergy. They presented that the gas turbine combustion chamber generates the greatest exergy in the entire cycle so that the increased pressure ratio in the gas turbine compressor should reduce the loss of exergy in other components. Ameri et al. [16] performed an exergetic investigation on a 420 MW CCPP in Neka, Iran. They evaluated that the gas turbine, combustion chamber, HRSG, and duct burner are the major areas of irreversibility, accounting for 83 % of the power plant's total destruction of exergy. The primary source of destruction of exergy was indeed acknowledged as the gas turbine combustion chamber. Another area of exergy generation was the HRSG, which can decrease the power plant's exergy defect by employing some modification. Isam Aljundi [17] carried out an energy and exergy investigation in the power plant of Alhossein in Jordan and deduced that the destruction of exergy in the boiler can be minimized by lowering the fuel air ratio and preheating the air infiltrating in the boiler. Ameri et al. [18] performed an energy and exergy investigations in Hamedan's steam power plant. The author examined the impact of tweaks in unit load and variations in ambient temperature on overall cycle performance and indicated that preheating the air approaching the boiler leads to an efficiency improvement and it is superior than the power plant usually operates in its marginal load to improve the efficiency.

Elsafi [19] carried out an exergy and exergoeconomic assessment on solar power plants for sustainable direct steam production. The author articulated exergy and exergy - expense formulae established on the principle of fuel contents for each element of the plant. Zhai et al.[20] applied the systemic thermo-economic principle assisted with solar energy in a coal-fired power plant. Author described the performance of the plant for both fuel saving and energy increasing approach. They postulated a 15.04 g / kWh reduction for consumption in the fuel-saving approach. In energy increasing approach, the energy output is 57.2 MW higher. They discovered that due to huge investments in solar energy, the thermal economic price of electricity has increased. Li et al. [21] used sub-critical, super-critical, ultra-supercritical steam conditions in power systems to compare energy and exergy. Parikhani et al. [22] carried out an energy, exergy and exergyeconomic investigation on a geothermal plant capacity of 2.33 MW, which is a combination of cooling, and power cycle. They proposed to assess the energy and exergy performance of cogeneration system of the plant. Mitrović et al. [23] portrayed an energy and exergy assessment of a 348.5 MW steam driven power plant in Kostolac in Serbia and observed that the irreversibility in the boiler is greater than the irreversibility in the other modules. Hagi et al. [24] addressed a performance evaluation of oxy coal power plants of the first generation using an exergetic technique for process unification. The capability for process development is pinpointed by the exergy analysis of the plant with limited assimilation and a methodology for heat integration minimizes the destruction of exergy. Rosen and Dincer[25] performed an exergoeconomic analysis of different fuel power plants. The connection between capital costs and thermodynamic deficits has been explored in their work.

Gonca [27] reported an energy and exergy investigation for a single and double reheat irreversible Rankine cycle. Author predicted thermal efficiency, exergy destruction, exergy efficiency and net specific work output. Erdem et al. [28] carried out a rigorous energy and exergy performance investigation for nine coal fired thermal power plant. The authors developed a comparison to investigate the inefficiency of the process in the plant and recommended furthered modification. In their work, they was able to determine the source of main irreversibility's in the system component and indicated necessary remodelling of the plant. Ehyaei et al. [29] researched exergy, environmental and economic evaluation in order to confirm the impacts of the inlet fogging system on the efficiency of first and second law for a conventional gas turbine power plant.

This paper is based on the energy and exergy investigation in the boiler of a 210 MW gas fired thermal power plant, which is owned and maintained by Bangladesh Power Development board (BPDB). This article analyzes the energy efficiency and exergy efficiency of the boiler by utilizing the first and second law of thermodynamics. The another objective of this work is to determine the rate of exergy destruction by the boiler in the power plant.

II. POWER PLANT DESCRIPTION

The power plant have been investigated in this work is the oldest power plant in Bangladesh which is known as Chittagong Power Station located 16 miles away from the Chittagong town and north-east side of the city. It is a government own gas fired thermal power plant with an install capacity of 210 MW. The power plant comprises of two steam turbine units, which makes a total capacity of 420 MW at full load condition. The power plant two steam turbine unit (2*210) at 100% load capacity. Operating cycle of this power station is Rankine cycle and an operating flow diagram is presented in Fig. 1. The approximate cycle efficiency of the power plant is 32%. The air-fuel ratio was used in the chamber as 10:1 for full combustion.

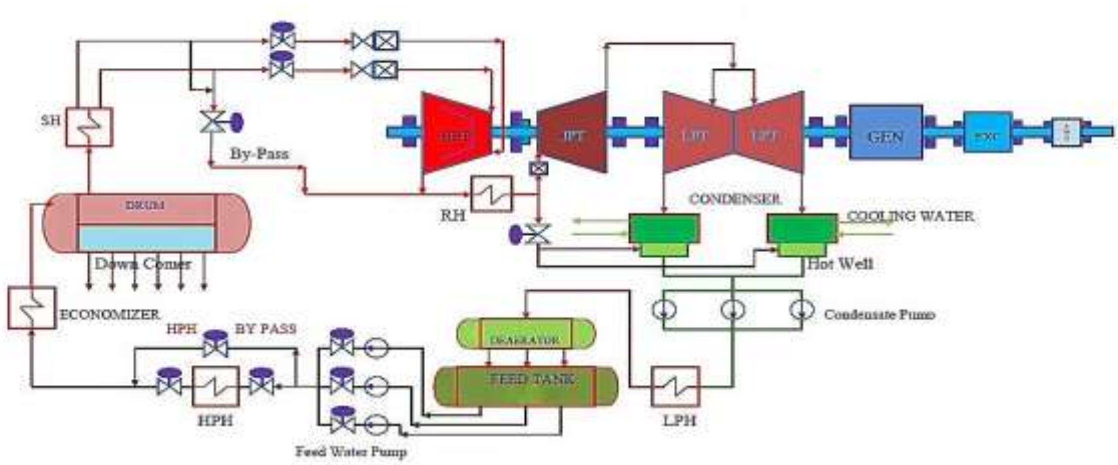

Fig. 1: Process flow diagram of the power plant

III. Data analysis and modelling

A. Energy and Exergy Analysis in Boiler

In order to examine energy and exergy in the power plant cycle, the data available in the power plant repository is used to evaluate thermodynamic constraints needed for all cycle points under design conditions. Values of unknown quantities is determined using conservation of energy principle and exergy equations. Figure 2 shows a schematic diagram for energy and exergy analysis in the boiler.

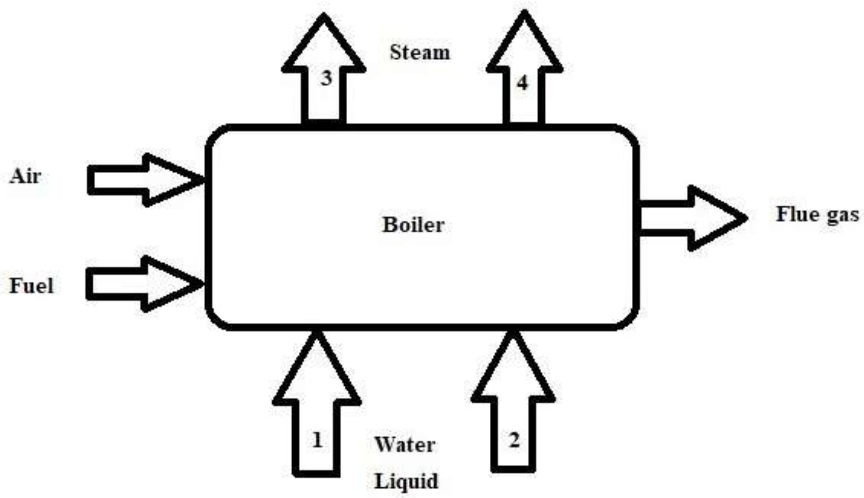

Fig. 2: Schematic diagram of the boiler

Exergy analysis determines maximum available work potential of energy and is determined at a reference ambient condition. For the boiler exergy analysis, it is assumed that the rate of change in exergy is zero. Throughout the combustion of methane in the combustion chamber, methane is used as fuel and the preceding chemical reaction takes place:

$$CH_4 + 2(O_2 + 3.76N_2) = CO_2 + 2H_2O + 7.52N_2 \tag{1}$$

Energy supplied by fuel

$$E_f = m_f * LHV \tag{2}$$

Where, m_f is the mass flow rate of fuel and LHV is the fuel's lower heating value. Water and steam mass balance

$$m_1 + m_2 = m_3 + m_4 \tag{3}$$

Where m_1, m_2, m_3 and m_4 are mass flow rate of water and steam at 1,2,3 and 4 respectively. Energy gain by steam

$$E_S = m_3(h_3 - h_1) + m_4(h_4 - h_2) \tag{4}$$

Where, h_1, h_2, h_3 and h_4 are enthalpies at point 1, 2, 3 and 4

Exergy of water at inlet 1

$$Ex_1 = h_1 - T_0 * s_1 \tag{5}$$

Exergy of water at inlet 2,

$$Ex_2 = h_2 - T_0 * s_2 \tag{6}$$

Exergy of steam at outlet 3,

$$Ex_3 = h_3 - T_0 * s_3 \tag{7}$$

Exergy of steam at outlet 4,

$$Ex_4 = h_4 - T_0 * s_4 \tag{8}$$

Here, T_0 is the ambient temperature and s_1, s_2, s_3 and s_4 are entropies at 1, 2, 3 and 4.

Steam exergy gain

$$E_{xS} = m_3(Ex_3 - Ex_1) + m_4(Ex_4 - Ex_2) \tag{9}$$

Dincer et al.[30] identified that specific exergy of hydrocarbon fuels is reduced to chemical exergy under near-environmental conditions and can be written as follows

$$E_{xf} = \gamma_{ff} * m_f * H_{ff} \tag{10}$$

Where γ_{ff} signifies the feature of the fuel exergy class, the ratio of the fuel chemical exergy and heating value and H_{ff} is known as the heating value. Table 1 shows typical values of H_{ff} and γ_{ff} for the fuels encountered in this study.

Table I
PROPERTIES OF SELECTED FUEL [31]

Fuel	**LHV (kJ/Nm^3)**	**Chemical exergy (kJ/kg)**	**Exergy grade function, γ_{ff}**
Natural gas	37183.21	34580.39	0.93

Energy efficiency of boiler

η_{Boiler} = Energy gained by steam/Energy supplied by fuel

$$\eta_{Boiler} = \frac{m_3(h_3 - h_1) + m_4(h_4 - h_2)}{m_f * LHV} \tag{11}$$

Exergy efficiency of boiler

Ψ_{Boiler}= Exergy gained by steam/Exergy supplied by fuel

$$\Psi_{Boiler} = \frac{m_3(Ex_3 - Ex_1) + m_4(Ex_4 - Ex_2)}{\gamma_{ff} * m_f * LHV} \tag{12}$$

Exergy Destruction of boiler,

$$\dot{I}_{Boiler} = Exergy\ produced\ by\ fuel - Exergy\ gained\ by\ steam$$

$$\dot{I}_{Boiler} = E_{xf} - E_{xS} \tag{13}$$

B. Data collection

Mass flow rate, temperature and pressure at different location of the boiler was collected from the archive of the power plant to calculate energy and exergy parameters. Thermodynamics properties of the refrigerant is determined using REFPROP 7 package software. Table 2 shows the collected data from the archive and calculated thermal properties at different load condition.

TABLE II
COLLECTED DATA

Load (MW)	m_3 (kg/s)	m_4 (kg/s)	m_f (kg/s)	T_1 (K)	T_2 (K)	T_3 (K)	T_4 (K)	P_1 (MPa)	P_2 (MPa)	P_3 (MPa)	P_4 (MPa)
90	39.82	39.82	6.92	483	483	808	807	12.9	12.9	12.2	12.2
100	43.09	42.84	7.53	486	486	806	804	12.9	12.9	12.2	12.2
110	47.12	47.88	8.36	492	492	806	804	13	13	12.2	12.2
160	66.02	66.27	10.92	506	506	805	804	13.2	13.2	12.3	12.3
170	72.32	71.82	12.11	509	509	805	805	13.4	13.4	12.3	12.3
180	74.34	74.34	12.78	512	512	805	804	13.4	13.4	12.4	12.4

IV. RESULTS AND DISCUSSIONS

In this study, the energy and exergy efficiency of a steam power station boiler is studied. Energy provided by the fuel and combustion energy efficiency have been studied. Exergy investigation includes exergy destruction and exergy efficiency of the combustor. Data was recorded from the steam power plant and Equations 2-13 have been used to calculate energy and exergy parameters of the boiler. Figure 3 shows the energy efficiency of the boiler at different load condition. Figure shows that, thermal efficiency of the boiler is different at different load condition and thermal efficiency is maximum for a 160 MW load condition. The designed energy efficiency of the boiler is 87.16%. The variation in exergy gain by steam at different load condition is demonstrated in Figure 4. Exergy gain by steam is increasing with the increase of load as at different load condition mass flow of the steam is different. Figure 5 shows the exergy supplied by the fuel at different load conditions.

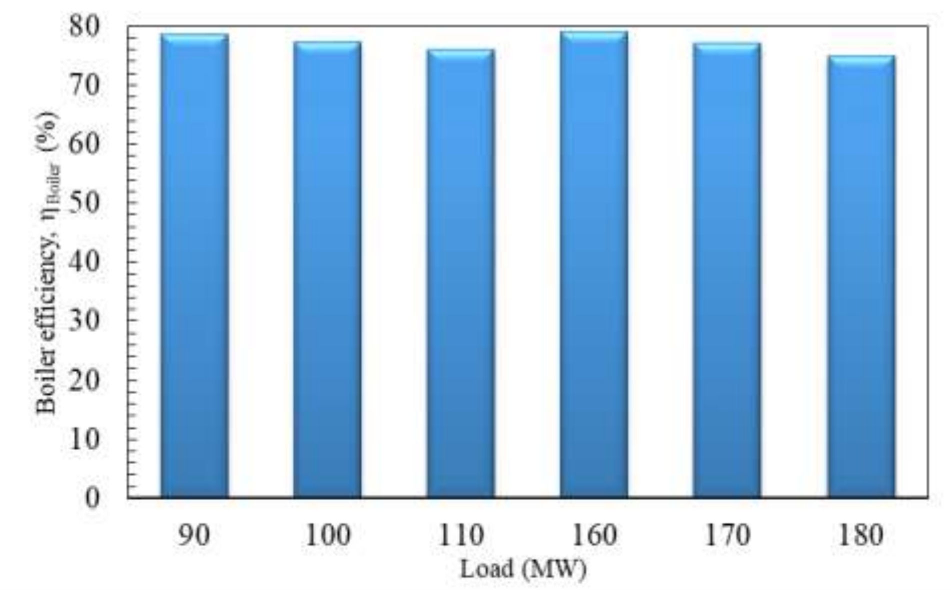

Figure 3. Variation of boiler energy efficiency at different load

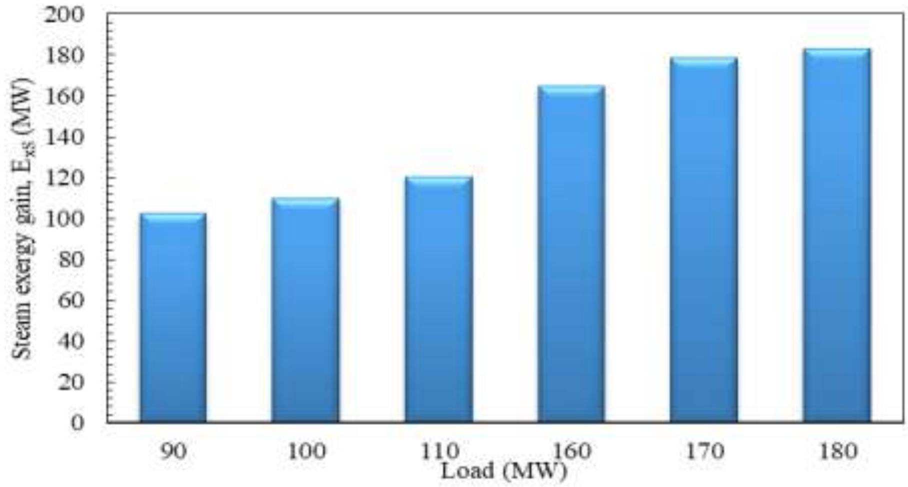

Figure 4. Exergy gain by steam at different load condition

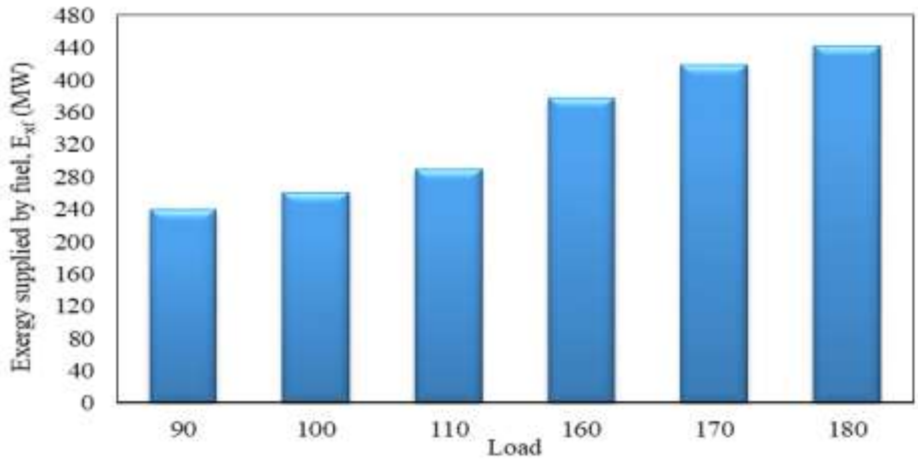

Figure 5. Exergy supplied by fuel

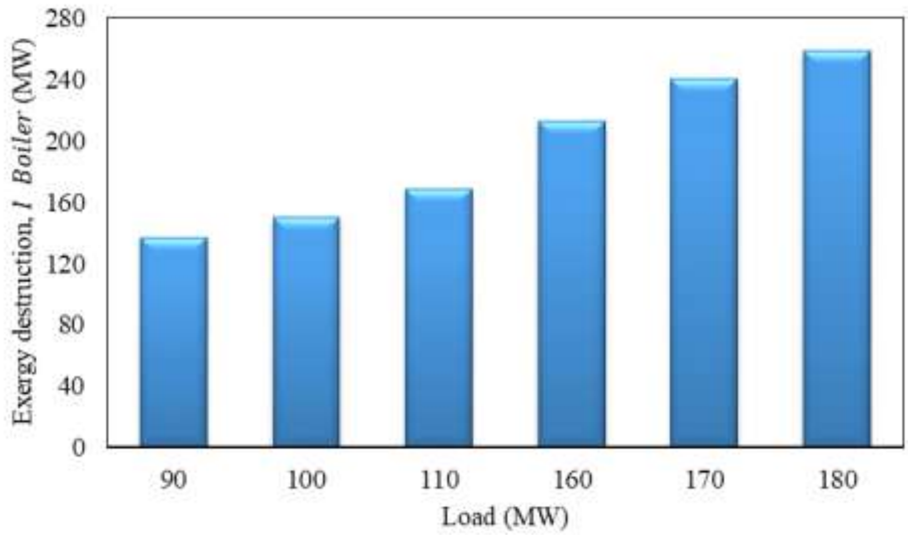

Figure 6. Variation of exergy destruction at different load

Figure 7 shows the variation of exergy efficiency of the boiler at different load condition. Exergy efficiency of the boiler remain almost similar at every load condition. Exergy efficiency is found to be maximum for a load of 160 MW.

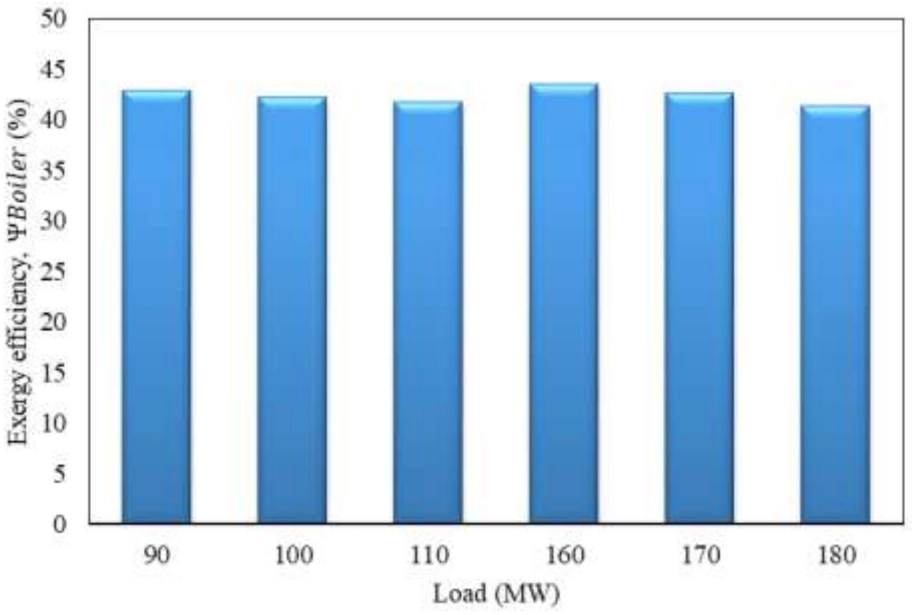

Figure 7. Variation in exergy efficiency

V. Conclusions

Energy and exergy of boiler in a 420 MW steam power at Bangladesh have been studied. Energy efficiency, exergy efficiency, exergy gain, exergy destruction at different load condition has been reported. From the above findings, the following conclusions can be drawn:

- The overall energy efficiencies vary from 75% to 80% and exergy efficiencies varies from 41.4 % to 43 % for boiler.
- Energy efficiency and exergy efficiency reached at a maximum value during the load of 160 MW.
- Exergy destruction rate in boiler is maximum during the load 180 MW.
- Exergy destruction rate is higher for higher load condition.

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