Exergy Analysis of a Steam Power Plant

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Abstract: An energy and exergy analysis as well as the effect of varying the reference environment temperature on the exergy analysis of an actual steam power plant has been carried out. Simulation methodology of power generation cycle has been employed to perform analysis of case study. The results show, the maximum energy lost in the condenser where 129 MW, while the maximum value of the exergy destruction was found in the boiler system 115 MW. In addition, the calculated thermal efficiency based on the lower heating value of fuel was 27% while the exergy efficiency of the power cycle was found 25%. Consequently, the boiler is the major source of irriversibilities in the system, even though, the percent exergy destruction and the exergy efficiency of each component in the system changed with reference environment temperature.

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1. Introduction

Research shows that there is a direct relation between the level of development of a country and quantity of energy consumption. Analysis of power generation systems are of scientific interest and also essential for the efficient utilization of energy resources. Steam power plants are widely utilized throughout the world for electricity generation and heavy fuel oil (HFO), coal, nuclear and natural gas is often used to fuel these plants. To utilize (HFO) more effectively, efficiently and cleanly in electricity generation processes, efforts are often expended to improve the efficiency and the performance of existing plants through modifications and retrofits, and develop advanced (HFO) utilization technologies (Dincer and Rosen, 2007).

The most commonly used method for analysis is energy and exergy analysis of power generation systems and improve the efficiency of the plant. In recent decades, uses the second law of thermodynamics in conjunction with energy analysis, via exergy methods analysis has found increasingly widespread acceptance as a useful tool in the design, assessment, optimization and improvement of energy systems efficiency (Dincer and Rosen, 2007, Kotas, 1985). Exergy analysis be able to determine the largest losses of the process based on the performance evaluation of the system and then improves efficiency of the thermal systems (Rosen and Dincer, 2004).

In this survey, energy and exergy analyses will be utilized to examine and better understand the performance of steam power plants, and will be identified and evaluate the performance of the components separately as well as whole plant to improve the plant efficiencies. Schematic of the case study power plant for the steaming process will be proposed. Exergy is useful for providing a detailed breakdown of the losses, in terms of waste exergy emissions and irreversibility, for the overall plants and their components. The challenge consisted of simulating a real thermal power plant, currently in operation.

To illustrate this approach consider of a conventional Rankine steam cycle through mass, energy and exergy balance for every components of the plant, based on the data of an operating steam power plant, with a power output of 64 MW. The data obtained of this analysis employed to get the energy and exergy efficiency of every component and whole of the plant.

The exergy method of analysis overcomes the limitations of the first law of thermodynamics. The exergy analysis is based on both the First and the Second Laws of Thermodynamics. Exergy analysis can clearly indicate the locations of energy degradation in a process that may lead to improved operation. The main purpose of exergy analysis is to identify the causes and to calculate the true magnitudes of exergy losses.

The utilization of energy and exergy analysis of a steam power plant is developed by very fundamental works of the early years such as (Bejan, 1948) that carried out exergy method to evaluate the performance of thermal systems in a wide range particularly, involves investigating located of entropy generation, or exergy destruction based on the losses in power plant. The first and second low performance, as well as thermo economic analysis of fossil fuel superheated nuclear power plant was examined in India by (Noam, 1997). Recently, exergy studies have evaluated the performance of power plants, as a means to optimize the performance and estimate the efficiency of the plant (Marc A, 2001) assessed the performance of coal-fired and nuclear power plants via exergy analysis. (Sengupta et al., 2007) evaluated an exergy analysis of a 210MW thermal power plants (Regulagadda et al., 2010) evaluated exergy analysis of thermal power plant with measured boiler and turbine losses. A multi objective study represents the energy and exergy analysis of the steam power plant in Jordan including, analysis the system components separately, estimates the system performance, investigates the environment impact on the system analysis was done by (Aljundi, 2009).

Unlike these past studies, this current research presents an exergy analysis of a uniquely configured Rankin cycle operating in subcritical situations. The generator power output is 64 MW. The boiler is a natural circulating that the bed combustor fueled with heavy fuel oil (HFO) with a capacity of 300 (t/h) of steam at 100% BMCR at the rated steam parameters. The power plant is designed to utilize an air cooled condenser to condense the exhaust steam.

The objective of this work is to examine Iranshahr power plant from an energy and exergy aspects. So the study seeks to address the following matters:

1) To perform an energy and exergy balance on each component of the plant.
2) To evaluate the first and second low efficiency of the whole unit.
3) To investigate the effect of varying the reference environment state on the exergy analysis.

The scope of the research is to perform a thermodynamic exergy analysis, for one unit of an actual power plant under construction in Iran. There are considered simulation method of the unit by the ideal Rankin power generating cycle. The operating data collected directly from the plant under study to analysis.

2. Plant Specification

The power plant has a total installed power capacity of 256MW. It is located 700m above sea level in the city of Iranshahr, south east of Iran 1500km of Tehran. It started to produce power in the middle nineties. The power house consists of four steam turbines units (4x64) MW at 100% load. The power uses heavy fuel oil, which is obtained from a nearby oil refinery. The annual fuel consumption in the year 2010 is 560,000 tons. Properties for the heavy fuel oil obtained in the month march, 2011 are shown in **Table 1**. Operating data those obtained from Iranshahr steam power plant tabulated in **Table 2**. Schematic diagram of one 64MW unit is shown in **Figure 1.** This unit employs regenerative feed water heating system. Feed water heating is carried out in two stages of high pressure heaters (HPH1, HPH2) and two stages of low pressure heaters (LPH1, LPH2) along with one deaerating heat exchanger. Steam is superheated to 808 K and 12.9 MPa in the steam generator and fed to the turbine. The turbine exhaust steam is sent to an air-cooled condenser and the condensate to the condensate return tank (CRT). Then, the cycle starts over again. Dead state properties evaluated at temperature 33 °C and pressure 101.30 KPa.

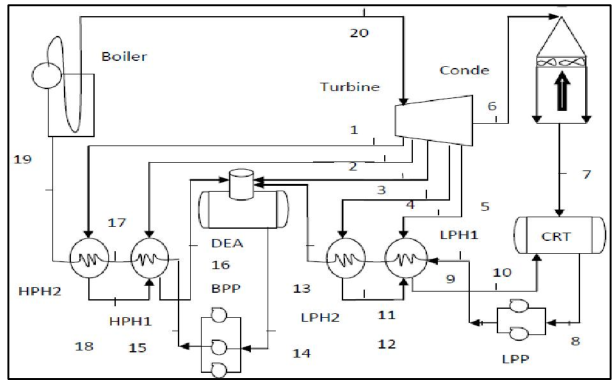


Figure 1 schematic flow diagram the steam power plant

Table 1: Properties of heavy fuel oil used in Iranshahr plant for March2011

Property	Value
Density at 15°C	0.96 g/mL
Total sulfur	3.03 wt%
Flash point	83 °C
Kinematic viscosity @100°C	732.3 mm^2/s
Pour point	18 °C
Ash content	1.44 wt%
Water and sediment	52 v%
Gross calorific value	42563.088 kJ/kg
Net calorific value	40518.120 kJ/kg

Table 2: Operating conditions of Iranshahr power plant

Operating condition	Value
Mass flow rate of fuel	4.8 kg/s
Stack gas temperature	160 °C
Feed water inlet temperature to boiler	232 °C
Steam flow rate	267 ton/h
Steam temperature	535 °C
Steam pressure	12.9 MPa
Power output	54 MW
Power input to ACC/fan	110 kw
Number of fans	9
Combined pump/motor efficiency	0.95
Inlet gas volumetric flow rate to burners	155,850 Nm3/h
Mass flow rate of cooling air	21,600 ton/h

3. Analysis

The main purpose of the research is to investigate energy and exergy analysis an actual steam power plant which in fact in operation. By using the simulation method, simulation of the plant with ideal thermodynamic steam power Rankin cycle, based on the operating data, and perform mass, energy and exergy balance of every components of the plant in flow diagram. Based on the properties of every point, energy and exergy analysis will be done.

Mass, energy, and exergy balances for any control volume at steady state with negligible potential and kinetic energy changes will be expressed, respectively, by (Aljundi, 2009).

$$\sum \dot{m}_i = \sum \dot{m}_e \quad (1)$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_e h_e = \sum \dot{m}_i h_i \quad (2)$$

$$\dot{I} = \dot{X}_{heat} - \dot{W} + \sum \dot{m}_i \psi_i - \sum \dot{m}_e \psi_e \quad (3)$$

Where the net exergy transfer by heat ($\dot{X}_{heat}$) at temperature T is given by

$$\dot{X}_{heat} = \sum \left(1 - \frac{T_0}{T}\right) \dot{Q} \quad (4)$$

And the specific exergy is given by

$$\psi = h - h_0 - T_0(s - s_0) \quad (5)$$

Then the total exergy rate associated with a fluid stream becomes

$$\dot{X} = \dot{m}\psi = \dot{m}[h - h_0 - T_0(S - S_0)] \quad (6)$$

Choosing each component of the plant in **Figure 1**, as a control volume, in the steady state condition the exergy destruction rate and the exergy efficiency will be obtained as shown in **Table 3**. The exergy efficiency of the power cycle may be defined in several ways, in this case the exergy destruction associated with fuel combustion considered and exergy lost with exhaust gases from the furnace as well (Ameri et al., 2009, Aljundi, 2009). The fuel specific exergy will be calculated as, $\psi_{fuel} = \xi_f \times LHV$, where $\xi_f = 1.06$, is the exergy factor based on the lower heating value. In addition, the pump input power will be calculated as, $\dot{W}_{pump} = \frac{\dot{m}(h_{e,s} - h_i)}{\eta_{combined}}$, where $\eta_{combined} = 0.95$, is the combined pump/motor efficiency (Isam H, 2009). Energy and exergy efficiencies will be evaluated as ratios of products to inputs. For the overall stations, the energy efficiency η is evaluated as

$$\eta = \frac{\text{Net energy output with electricity}}{\text{Energy input}} \quad (7)$$

the exergy efficiency ψ as

$$\psi = \frac{\text{Net exergy output with electricity}}{\text{Exergy input}} \quad (8)$$

For most of the other plant components and sections, similar expressions will be applied to evaluate efficiencies. Efficiencies will not be readily defined for the condensers, as the purpose of such devices is to reject waste heat rather than generate a product. However, the merit of the condensers with respect to the overall plant can be assessed for comparative purposes by evaluating the 'net station condenser heat (energy) rejection rate' R_{energy}, where

$$R_{energy} = \frac{\text{Heat rejected by condencer}}{\text{Net exergy produced}} \quad (9)$$

There are many conventional simulators for steam power plants which arrange the mass and thermal balances of the subsystems of the plant, thus its giving energy performance. These programs can lead to obtain the exergies and give the exergy efficiencies of each component. This information is more useful, both for designing new installations and for controlling and diagnosing real operating plants. So it is necessary to generate models as close to reality as possible. The results from fist law and second law analysis gives couple function; those are the thermal inefficiencies and exergy efficiency of the various subsystems. Thus these functions will be used to determine optimum operation of the plant (Kanoglu et al., 2007).

4. Finding and Discussion

Energy and exergy balances are applied to components of the case study, for the operation data given in **Table 2**. The results of these balances are tabulated in **Table 3.** Analysis of the power plant has been done by employing the previous section relations to calculate at 306 K and 101.3 KPa as the environment reference temperature and pressure respectively. The thermodynamic properties of water and air were determined at every point in flow diagram of the plant, **Figure 1**; the results are summarized in **Table 3**. Based on the methodology procedure it is follow energy balances for every case and tabulated in **Table 4**. It shows that the thermal efficiency is (27%). This efficiency is based on using lower heating value of the fuel to contain the losses taking place in the combustor of boiler system which reasons energy lost with hot gases, incomplete combustion, etc. The energy balance also reveals that two thirds of the fuel energy is lost in the condenser and carried out into the environment, while only 7% is lost in the boiler. However, efficiencies based on energy can often be obtained indirectly or even misinforming (Rosen, 2002), partly due to it does not give a measure of idealistic. Moreover, losses of energy can be large quantity while it is thermodynamically inconsiderable due to its low quality. Exergy-based efficiencies and losses, however, provide measures of approach to ideality or deviation from ideality. Exergy analysis results that includes percent of exergy destruction along with the exergy efficiencies, for all cases individually and whole the plant summarized in **Table 5**. The exergy destruction rate of the boiler is the main over all other irreversibilities in the cycle. It is noticeable that counts alone for 76% of losses in the plant; otherwise the exergy destruction rate of the condenser is just 9%. Even though, based on the first low analysis, energy losses associated with the condenser are noticeable with amount 66% of the energy input the plant. However, results of an exergy analysis showed that, just 9% of the exergy was lost in the condenser; the real loss is basically backed in the boiler where entropy was generated. Opposite to the first law analysis, the second law analysis shows that there is an important improvement in the boiler system comparatively in the condenser. To more illustrate of issues, the results represented graphically. The exergy destruction of all components showed individually in **Figure 2 (a),** by chart as well as**,** the exergy efficiency of every component represented in **Figure 2 (b).** The calculated exergy efficiency of the power cycle is 25%, which is low. This shows that huge opportunities are accessible for improvement. However, part of this irreversibility cannot be avoided due to physical, technological, and economic restrictions.To quantify the exergy of the system, it is required that to specify together the system and the surroundings. In any process it is assumed that the intensive properties of the environment are not notably changed by any process. The dead state of a system in which it is at equilibrium with its surroundings. When a system and its surroundings is at the same temperature, pressure, velocity and chemical composition, in case of investigation of useful work there is no potential differences exist (Rosen and Dincer, 2004). Based on the fist law analysis the reference environment state is not relevant for calculating a change in a thermodynamic property. However, based on the second law analysis it is expected that the dead state will have some effects on exergy analysis results. Even though, some researchers logically assumed that small changes in dead-state properties have little effect on the performance of a given system. To perceive how important this effect will be on the results, the dead-state temperature was changed from278.15 K to 318.15 K and the pressure has been at 101.3 KPa. Values of total exergy rates at different dead states for situations represented in **Figure 1** are summarized in **Table 6**. The results of main components represented in **Table 7** as the exergy destruction and in **Table 8** as the exergy efficiency of main components. For more illustration, sketched graphs in **Figure 3 (a)** and **Figure 3 (b)**, as a rate of exergy destruction and exergy efficiency changing respect to change reference environment temperature. The results show the major source of exergy destruction is the boiler but no matter of changing the references environment temperature. **Figure 3** shows that exergy efficiencies of the boiler and turbine did not change significantly with dead state temperature; nevertheless, the efficiency of the condenser at 318.15 K is almost as much as when the ambient temperature was 278.15 K. The reason can be explained by noting the reduction of temperature difference between the steam and the cooling air as

the dead state temperature is increased. There is cause and effect relation between decrease the exergy destruction and increase the exergy efficiency.

Table 3: Exergy analysis of the power plant when $T_0 = 306.15$ K, $P_0 = 101.3$KPa

Point	T(K)	P(MPa)	$\dot{m}$(kg/s)	h(kJ/kg)	s(kJ/kg)	ψ(kJ/kg)	$\dot{X}$(MW)
1	632.65	3.22	4.80	3133.694	6.7422	1077.50	5.172
2	546.85	1.446	4.02	2980.813	6.8335	896.673	3.605
3	433.15	0.58	4.42	2760.747	6.7847	691.547	3.057
4	418.15	0.369	3.76	2744.182	6.9459	625.631	2.352
5	382.05	0.136	1.74	2689.664	7.2583	475.472	0.827
6	351.15	0.0385	55.43	2640.599	7.6995	291.333	16.149
7	348.05	0.0385	55.43	313.554	1.0144	10.932	0.606
8	347.45	0.0375	60.94	311.039	1.0072	10.621	0.647
9	349.65	1.85	60.94	321.717	1.0325	13.553	0.826
10	362.35	0.07	5.51	373.605	1.1834	19.243	0.106
11	369.65	1.28	60.94	405.243	1.2664	25.471	1.552
12	378.35	0.123	3.77	441.059	1.3654	30.978	0.117
13	399.65	0.31	60.94	531.500	1.5974	50.392	3.071
14	433.15	0.619	74.17	675.575	1.9428	88.723	6.581
15	434.95	16.55	74.17	692.769	1.9421	106.131	7.872
16	439.65	0.728	8.82	703.898	2.0074	97.269	0.858
17	466.95	14.55	74.17	830.566	2.2527	148.838	11.039
18	480.65	3.13	4.80	886.816	2.3991	160.268	0.769
19	501.35	13.89	74.17	984.445	2.5722	204.902	15.198
20	808.15	12.90	74.17	3432.904	6.5648	1431.00	106.140
Input air	306.15	0.1013	6000	306.650	6.8892	0.000	0.000
Output air	326.15	0.1013	6000	326.767	6.9529	0.615	3.691
Dead state	306.15	0.1013	-	138.373	0.4779	-	-

Table 4: Results of energy balance of the power plant components and percent ratio to fuel energy input

Component	Heat loss (KW)	Percent ratio (%)
Condenser	128,990	66.36
Net power	52000	26.75
Boiler	12,884	6.63
Heaters	515.3	0.27
Total	194,389	100

Table 7: Exergy efficiency of main components at different reference environment temperatures (%)

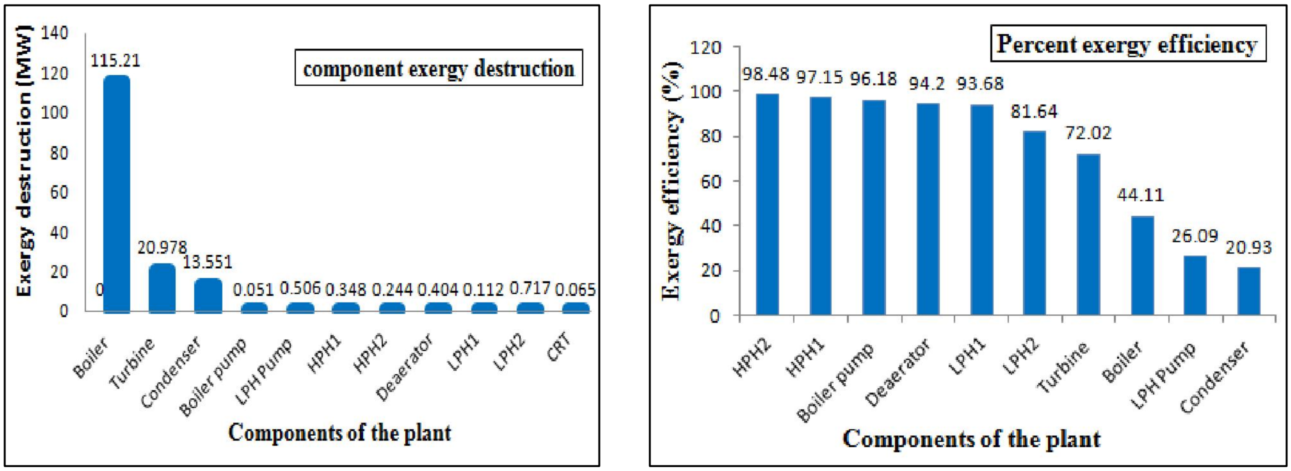
Component	278.15	283.15	288.15	293.15	298.15	303.15	308.15	313.15	318.15
Boiler	48.14	47.42	46.7	45.98	45.26	44.54	43.83	43.11	42.39
Turbine	73.91	73.57	73.22	72.89	72.55	72.22	71.89	71.56	71.24
Condenser	16.18	16.58	17.12	17.84	18.76	20.01	21.64	23.83	26.87

Table 5: Exergy destruction and exergy efficiency of the power plant components

Component	Exergy destruction (MW)	Percent exergy destruction	Percent exergy efficiency
Boiler	115.210	75.70	44.11
Turbine	20.978	13.78	72.02
Condenser	13.551	8.90	20.93
Boiler pump	0.051	0.035	96.18
LPH Pump	0.506	0.332	26.09
HPH1	0.348	0.229	97.15
HPH2	0.244	0.160	98.48
Deaerator	0.404	0.265	94.20
LPH1	0.112	0.074	93.68
LPH2	0.717	0.471	81.64
CRT	0.065	0.043	90.91
Power cycle	152.19	100.00	25.22

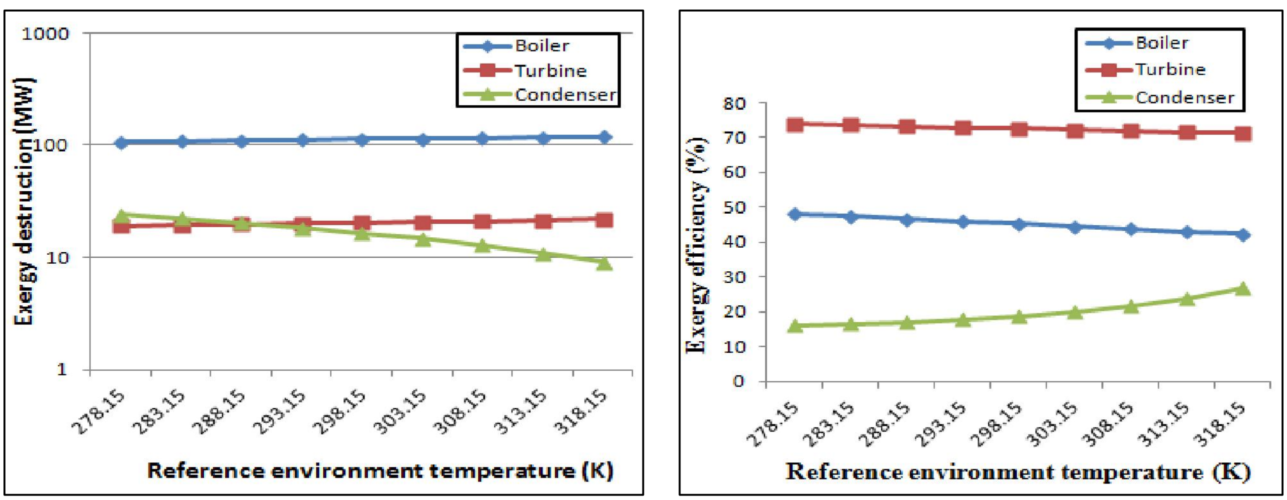
Table 6: Exergy destruction of main components of at different reference environment temperatures, (MW)

Component	278.15	283.15	288.15	293.15	298.15	303.15	308.15	313.15	318.15
Boiler	106.92	108.40	109.88	111.36	112.84	114.33	115.81	117.29	118.77
Turbine	19.061	19.404	19.746	20.089	20.43	20.772	21.115	21.457	21.799
Condenser	24.018	22.149	20.28	18.411	16.542	14.673	12.803	10.934	9.065



a) b)

Figure 2: (a) Exergy destruction, (b) Exergy efficiency of every components of the plant



a) b)

Figure 3: Effect of reference environment temperature on (a) the exergy destruction (b) the exergy efficiency of major plant components

5. Conclusion

In this paper, steam power plant systems were explored by energy and exergy analysis as well as the effect of varying the reference environment temperature on the exergy analysis of an actual steam power plant. Simulation methodology of power generation cycle was discussed and it was applied to case study.

In the considered power cycle, the maximum energy loss was found in the condenser where 66% of the input energy was lost to the environment. Next to it was the energy loss in the boiler system where it was found to be about 7%. In addition, the calculated thermal efficiency of the cycle was 27%. On the other hand, the exergy analysis of the plant showed the lost energy in the condenser is thermodynamically insignificant due to its low quality. In terms of exergy destruction, the major loss was found in the boiler system where 76% of the fuel exergy input to the cycle was destroyed. Next to it was the turbine where 21 MW of exergy was destroyed which represents 14% of the fuel exergy input to the cycle. The percent exergy destruction in the condenser was 9%.

The exergy efficiency of the power cycle that obtained was 25%, which it is lower than modern power plants. Due to the chemical reaction during the combustion process of the boiler system includes the highest value of exergy destruction associated to the excess air fraction and the temperature of the air at the inlet. As a maim result, the boiler is the major source of irriversibilities in the system, even though, the percent exergy destruction and the exergy efficiency of each component in the system changed with reference environment temperature.

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