Energy and exergy analysis of a steam power plant in Jordan

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ABSTRACT

In this study, the energy and exergy analysis of Al-Hussein power plant in Jordan is presented. The primary objectives of this paper are to analyze the system components separately and to identify and quantify the sites having largest energy and exergy losses. In addition, the effect of varying the reference environment state on this analysis will also be presented. The performance of the plant was estimated by a component-wise modeling and a detailed break-up of energy and exergy losses for the considered plant has been presented. Energy losses mainly occurred in the condenser where 134 MW is lost to the environment while only 13 MW was lost from the boiler system. The percentage ratio of the exergy destruction to the total exergy destruction was found to be maximum in the boiler system (77%) followed by the turbine (13%), and then the forced draft fan condenser (9%). In addition, the calculated thermal efficiency based on the lower heating value of fuel was 26% while the exergy efficiency of the power cycle was 25%. For a moderate change in the reference environment state temperature, no drastic change was noticed in the performance of major components and the main conclusion remained the same; the boiler is the major source of irreversibilities in the power plant. Chemical reaction is the most significant source of exergy destruction in a boiler system which can be reduced by preheating the combustion air and reducing the air–fuel ratio.

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1. Introduction

Jordan's energy market is one of the country's fastest developing sectors. Annual demand for electricity has increased by more than 9% during recent years, and installed capacity and annual generation figures have reached in 2006 approximately 9000 GW h [1]. Central Electricity Generating Company (CEGCO) is the sole power generating company in the country using heavy fuel oil, diesel, gas, and renewable resources. The power plants are distributed over most of the Jordanian cities, all of which are transmitting power through overhead lines of 132 and 400 kV.

Analysis of power generation systems are of scientific interest and also essential for the efficient utilization of energy resources. The most commonly-used method for analysis of an energy-conversion process is the first law of thermodynamics. However, there is increasing interest in the combined utilization of the first and second laws of thermodynamics, using such concepts as exergy and exergy destruction in order to evaluate the efficiency with which the available energy is consumed. Exergetic analysis provides the tool for a clear distinction between energy losses to the environment and internal irreversibilities in the process [2].

Exergy analysis is a methodology for the evaluation of the performance of devices and processes, and involves examining the exergy at different points in a series of energy-conversion steps. With this information, efficiencies can be evaluated, and the process steps having the largest losses (i.e., the greatest margin for improvement) can be identified [3].

For these reasons, the modern approach to process analysis uses the exergy analysis, which provides a more realistic view of the process and a useful tool for engineering evaluation [4]. As a matter of fact, many researchers [5–8] have recommended that exergy analysis be used to aid decision making regarding the allocation of resources (capital, research and development effort, optimization, life cycle analysis, materials, etc.) in place of or in addition to energy analysis [3]. Exergy analysis has become a key aspect in providing a better understanding of the process, to quantify sources of inefficiency, and to distinguish quality of energy used [9]. Some researchers dedicated their studies to component exergy analysis and efficiency improvement [10,11]; others focused on systems design and analysis [12–16].

The objective of this work is to analyze Al-Hussein power plant from an energy and exergy perspective. Sites of primary energy loss and exergy destruction will be determined. The effect of varying the reference environment state (dead state) on the exergy analysis will also be investigated.

2. Plant description

The power plant has a total installed power capacity of 396 MW. It is located 560 m above sea level in the city of Zarqa,

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Nomenclature

h	specific enthalpy (J/kg)
$\dot{I}$	exergy destruction rate (W)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
$\dot{Q}$	heat transfer rate to the system (W)
s	specific entropy (J/kg K)
T	temperature (K)
$\dot{W}$	work rate or power done by the system (W)
$\dot{X}$	total exergy rate (W)

Greek symbols

η_{II}	exergy efficiency
Ψ	specific exergy (J/kg)
γ	exergy factor

Subscripts

e	exit
i	inlet
s	isentropic
o	dead state conditions
f	fuel

Table 1
Properties of heavy fuel oil used in Al-Hussein power plant for April 2007

Property	Value
Density at 15 °C	0.9705 g/mL
Total sulfur	3.76 wt%
Flash point	117 °C
Kinematic viscosity @ 100 °C	35.52 cSt
Pour point	+7 °C
Ash content	0.036 wt%
Water and sediment	0.14 V%
Gross calorific value	42943.81 kJ/kg
Net calorific value	40504.58 kJ/kg

at north east of Jordan 30 km of Amman. It started to produce power in the middle seventies. The power house consists of seven steam turbines units $(3 \times 33 + 4 \times 66)$ MW and two gas turbines $(1 \times 14 + 1 \times 19)$ MW at 100% load. The power plant uses heavy fuel oil, which is obtained from a nearby oil refinery. The annual fuel consumption in the year 2006 is 504,030 tons. Properties for the heavy fuel oil obtained in the month of April, 2007 are shown in Table 1.

The schematic diagram of one 66 MW unit is shown in Fig. 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 (LPH4, LPH5) along with one deaerating heat exchanger. Steam is superheated to 793 K and 9.12 MPa in the steam generator and fed to the turbine. The turbine exhaust stream is sent to an air-cooled condenser and the condensate to the condensate return tank (CRT). Then,
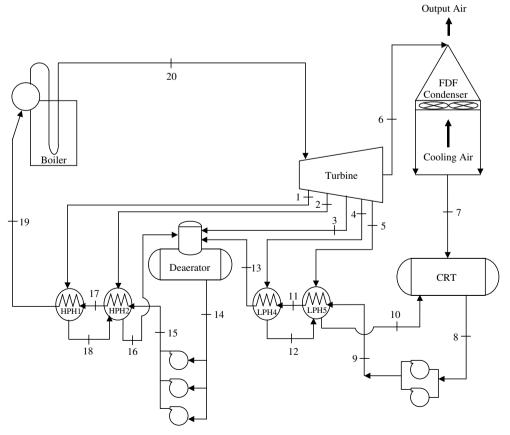

Fig. 1. Schematic diagram of the power plant.

Table 2
Operating conditions of the power plant

Operating condition	Value
Mass flow rate of fuel	5.0 kg/s
Inlet gas volumetric flow rate to burners	188,790 N m³/h
Stack gas temperature	411.15 K
Feed water inlet temperature to boiler	494.15 K
Steam flow rater	275 ton/h
Steam temperature	793.15 K
Steam pressure	9.12 MPa
Power output	56 MW
Power input to FDC/fan	88 kW
Number of fans	18
Mass flow rate of cooling air	23,900 ton/h
Combined pump/motor efficiency	0.95

Table 3
The exergy destruction rate and exergy efficiency equations for plant components

	Exergy destruction rate	Exergy efficiency
Boiler	$\dot{I}_{boiler} = \dot{X}_{fuel} + \dot{X}_{in} - \dot{X}_{out}$	$\eta_{II,boiler} = \frac{\dot{X}_{out} - \dot{X}_{in}}{\dot{X}_{fuel}}$
Pumps	$\dot{I}_{pump} = \dot{X}_{in} - \dot{X}_{out} + \dot{W}_{pump}$	$\eta_{II,pump} = 1 - \frac{\dot{I}_{pump}}{\dot{W}_{pump}}$
Heaters	$\dot{I}_{heaters} = \dot{X}_{in} - \dot{X}_{out}$	$\eta_{II,heaters} = 1 - \frac{\dot{I}_{heaters}}{\dot{X}_{in}}$
Turbine	$\dot{I}_{turbine} = \dot{X}_{in} - \dot{X}_{out} - \dot{W}_{el}$	$\eta_{II,turbine} = 1 - \frac{\dot{I}_{turbine}}{\dot{X}_{in} - \dot{X}_{out}}$
Condenser	$\dot{I}_{condenser} = \dot{X}_{in} - \dot{X}_{out} + \dot{W}_f$	$\eta_{II,condenser} = \frac{\dot{X}_{out}}{\dot{X}_{in} + \dot{W}_f}$
Cycle	$\dot{I}_{cycle} = \sum_{all\ components} \dot{I}_i$	$\eta_{II,cycle} = \frac{\dot{W}_{net,out}}{\dot{X}_{fuel}}$

the cycle starts over again. The operating conditions of the power plant are summarized in Table 2.

3. Analysis

Exergy is a measure of the maximum capacity of a system to perform useful work as it proceeds to a specified final state in equilibrium with its surroundings. Exergy is generally not conserved as energy but destructed in the system. Exergy destruction is the measure of irreversibility that is the source of performance loss. Therefore, an exergy analysis assessing the magnitude of exergy destruction identifies the location, the magnitude and the source of thermodynamic inefficiencies in a thermal system.

Table 5
Energy balance of the power plant components and percent ratio to fuel energy input

Component	Heat loss (kW)	Percent ratio
Condenser	133,597	65.97
Net power	53,321	26.33
Boiler	12,632	6.24
Piping	1665	0.82
Heaters	856	0.42
Turbine	452	0.22
Total	202,523	100

Mass, energy, and exergy balances for any control volume at steady state with negligible potential and kinetic energy changes can be expressed, respectively, by

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

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

$$\dot{X}_{heat} - \dot{W} = \sum \dot{m}_e \Psi_e - \sum \dot{m}_i \Psi_i + \dot{I} \tag{3}$$

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

$$\dot{X}_{heat} = \sum (1 - T_o/T)\dot{Q} \tag{4}$$

and the specific exergy is given by

$$\Psi = h - h_o - T_o(s - s_o) \tag{5}$$

Then the total exergy rate associated with a fluid stream becomes

$$\dot{X} = \dot{m}\Psi = \dot{m}[h - h_o - T_o(s - s_o)] \tag{6}$$

For a steady state operation, and choosing each component in Fig. 1 as a control volume, the exergy destruction rate and the exergy efficiency are defined as shown in Table 3. The exergy efficiency of the power cycle may be defined in several ways, however, the used definition will not only allow the irreversibility of heat transfer to the steam in the boiler to be included, but also the exergy destruction associated with fuel combustion and exergy lost with exhaust gases from the furnace [17].

Note that the fuel specific exergy is calculated as: $\Psi_{fuel} = \gamma_f \times$ LHV, where $\gamma_f = 1.06$, is the exergy factor based on the lower heating value [18]. In addition, the pump input power was calculated as

Table 4
Exergy analysis of the power plant when T_o = 298.15 K, P_o = 101.3 kPa

Point	T (K)	P (MPa)	$\dot{m}$ (ton/h)	h (kJ/kg)	s (kJ/kg K)	Ψ (kJ/kg)	$\dot{X}$ (MW)
1	618.55	2.4231	17.80	3118.1	6.8419	1082.748	5.354
2	547.85	1.3244	14.92	2986.9	6.8835	939.145	3.892
3	463.65	0.5690	16.40	2831.4	6.9511	763.490	3.478
4	394.35	0.2060	13.96	2707.7	7.1173	590.238	2.289
5	360.45	0.0628	6.39	2655.2	7.5169	418.597	0.743
6	343.15	0.0272	204.90	2626.9	7.8193	300.136	17.083
7	339.95	0.0272	204.90	279.66	0.91588	11.151	0.635
8	339.75	0.0270	226.00	278.82	0.9134	11.045	0.693
9	341.15	1.3734	226.00	285.79	0.9299	13.113	0.823
10	337.60	0.0245	21.10	269.81	0.8868	9.959	0.058
11	356.15	0.0536	226.00	347.61	1.1111	20.896	1.312
12	362.45	0.0687	13.96	374.09	1.1848	25.403	0.099
13	390.15	0.1815	226.00	491.08	1.4954	49.787	3.126
14	428.15	0.6867	275.00	653.88	1.8922	94.281	7.202
15	430.15	12.2630	275.00	669.49	1.8991	107.834	8.237
16	436.15	0.6671	32.70	688.52	1.9725	104.980	0.954
17	461.45	10.7910	275.00	804.43	2.2056	151.391	11.565
18	466.15	2.3544	17.80	821.28	2.2626	151.246	0.748
19	494.15	10.3010	275.00	950.46	2.5124	205.949	15.732
20	793.15	9.1233	275.00	3436.3	6.7168	1438.247	109.866
Input air	298.15	0.1013	23,900	424.54	3.8814	0.000	0.000
Output air	318.15	0.1013	23,900	444.68	3.9468	0.647	4.294
Dead state	298.15	0.1013	–	104.92	0.3672	0.000	–

Table 6
Exergy destruction and exergy efficiency of the power plant components when T_o = 298.15 K, P_o = 101.3 kPa

	Exergy destruction (MW)	Percent exergy destruction	Percent exergy efficiency
Boiler	120.540	76.75	43.8
Turbine	20.407	12.99	73.5
Condenser	13.738	8.75	26.4
Boiler pumps	0.220	0.14	82.5
CRT pump	0.331	0.21	28.2
HPH1	0.438	0.28	97.4
HPH2	0.359	0.23	97.2
Deaerator	0.355	0.23	95.3
LPH4	0.377	0.24	89.5
LPH5	0.295	0.19	67.3
Power cycle	157.059	100.00	24.8

$\dot{W}_{pump} = \dot{m}(h_{e,s} - h_i)/\eta_{combined}$, where $\eta_{combined}$ = 0.95, is the combined pump/motor efficiency.

4. Results and discussion

The power plant was analyzed using the above relations noting that the environment reference temperature and pressure are 298.15 K and 101.3 kPa, respectively. The thermodynamic properties of water and air at indicated nodes in Fig. 1 were calculated using REFPROP 8 software [19] and summarized in Table 4.

The energy balance of the power plant is presented in Table 5. It shows that the thermal efficiency (26%) is low compared to modern power plants. Clearly, this efficiency was not based on the specific heat input to the steam; rather, it was based on the lower heating value of the fuel to incorporate the losses occurring in the furnace-boiler system due to 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 6% is lost in the boiler. Nonetheless, efficiencies based on energy can often be non-intuitive or even misleading [20], in part because it does not provide a measure of ideality. In addition, losses of energy can be large quantity while it is thermodynamically insignificant due to its low quality. Exergy-based efficiencies and losses, however, provide measures of approach to ideality or deviation from ideality.
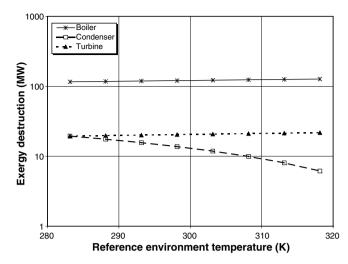

Fig. 2. Effect of reference environment temperature on total exergy destruction rate in major plant components.

Exergy and percent of exergy destruction along with the exergy efficiencies are summarized in Table 6 for all components present in the power plant. It was found that the exergy destruction rate of the boiler is dominant over all other irreversibilities in the cycle. It counts alone for 77% of losses in the plant, while the exergy destruction rate of the condenser is only 9%. According to the first law analysis, energy losses associated with the condenser are significant because they represent about 66% of the energy input to the plant. An exergy analysis, however, showed that only 9% of the exergy was lost in the condenser. The real loss is primarily back in the boiler where entropy was produced. Contrary to the first law analysis, this demonstrates that significant improvements exist in the boiler system rather than in the condenser.

The calculated exergy efficiency of the power cycle is 25%, which is low. This indicates that tremendous opportunities are available for improvement. However, part of this irreversibility can not be avoided due to physical, technological, and economic constraints.

In order to quantify the exergy of a system, we must specify both the system and the surroundings. It is assumed that the

Table 7
Total exergy rate at different reference environment temperatures, MW

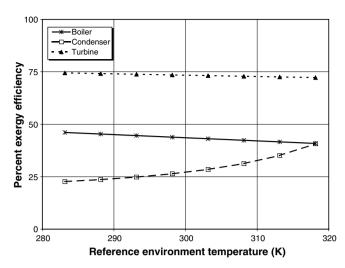| Point	Temperature (K)							
	283.15	288.15	293.15	298.15	303.15	308.15	313.15	318.15
1	5.842	5.677	5.515	5.354	5.194	5.037	4.881	4.727
2	4.304	4.165	4.028	3.892	3.758	3.625	3.494	3.363
3	3.935	3.781	3.629	3.478	3.329	3.181	3.035	2.891
4	2.688	2.553	2.420	2.289	2.159	2.030	1.902	1.776
5	0.936	0.871	0.807	0.743	0.680	0.617	0.555	0.494
6	23.536	21.365	19.213	17.083	14.972	12.881	10.809	8.756
7	1.195	0.987	0.801	0.635	0.489	0.362	0.254	0.166
8	1.309	1.081	0.876	0.693	0.533	0.394	0.276	0.180
9	1.454	1.221	1.011	0.823	0.658	0.514	0.391	0.289
10	0.113	0.093	0.075	0.058	0.044	0.032	0.022	0.014
11	2.113	1.823	1.556	1.312	1.089	0.888	0.709	0.550
12	0.152	0.133	0.115	0.099	0.083	0.069	0.057	0.046
13	4.289	3.878	3.491	3.126	2.783	2.461	2.160	1.881
14	9.072	8.421	7.798	7.202	6.633	6.090	5.573	5.082
15	10.115	9.462	8.836	8.237	7.666	7.120	6.600	6.107
16	1.187	1.106	1.028	0.954	0.882	0.814	0.749	0.687
17	13.794	13.023	12.280	11.565	10.876	10.213	9.576	8.966
18	0.896	0.845	0.796	0.748	0.702	0.658	0.615	0.574
19	18.313	17.425	16.565	15.732	14.926	14.146	13.392	12.665
20	117.264	114.771	112.305	109.866	107.454	105.069	102.709	100.375
Output air	4.509	4.435	4.363	4.294	4.227	4.162	4.100	4.039

Fig. 3. Effect of reference environment temperature on the exergy efficiency of major plant components.

intensive properties of the environment are not significantly changed by any process. The dead state is a state of a system in which it is at equilibrium with its surroundings. When a system is at the same temperature, pressure, elevation, velocity and chemical composition as its surroundings, there is no potential differences exist in such instances that would allow the extraction of useful work [3].

The reference environment state is irrelevant for calculating a change in a thermodynamic property (first law analysis). However, it is expected that the dead state will have some effects on the results of exergy (second law) analysis. Although, some researchers assumed that small and reasonable changes in dead-state properties have little effect on the performance of a given system. To find out how significant this effect will be on the results, the dead-state temperature was changed from 283.15 to 318.15 K while keeping the pressure at 101.3 kPa. Values of total exergy rates at different dead states for locations identified in Fig. 1 are summarized in Table 7. Results of such analysis show, in Fig. 2, that the major source of exergy destruction is the boiler no matter what the dead state is. Fig. 3 shows that exergy efficiencies of the boiler and turbine did not change significantly with dead-state temperature; however, the efficiency of the condenser at 318.15 K is almost twice as much when the ambient temperature was 283.15 K. This can be explained by noting the diminution of temperature difference between the steam and the cooling air as the dead-state temperature is increased. This will decrease the exergy destruction and hence, will increase the exergy efficiency.

5. Conclusions

In this study, an energy and exergy analysis as well as the effect of varying the reference environment temperature on the exergy analysis of an actual power plant has been presented. 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 6% and less than 2% for all other components. In addition, the calculated thermal efficiency of the cycle was 26%. On the other hand, the exergy analysis of the plant showed that 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 77% of the fuel exergy input to the cycle was destroyed. Next to it was the turbine where 20.4 MW of exergy was destroyed which represents 13% of the fuel exergy input to the cycle. The percent exergy destruction in the condenser was 9% while all heaters and pumps destroyed less than 2%.

The calculated exergy efficiency of the power cycle was 25%, which is low compared to modern power plants. The major source of exergy destruction was the boiler system where chemical reaction is the most significant source of exergy destruction in a combustion chamber. Exergy destruction in the combustion chamber is mainly affected by the excess air fraction and the temperature of the air at the inlet. The inefficiencies of combustion can be reduced by preheating the combustion air and reducing the air–fuel ratio.

Although the percent exergy destruction and the exergy efficiency of each component in the system changed with reference environment temperature, the main conclusion stayed the same; the boiler is the major source of irreversibilities in the system.

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