Research Article

Energy and Exergy Analysis of a Steam Power Plant in Sudan

Osman Shamet^{*1}, Rana Ahmed¹, Kamal Nasreldin Abdalla¹

¹Department of Mechanical Engineering, Faculty of Engineering, University of Khartoum, Sudan

*Corresponding author E-mail: osshamet@gmail.com

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Abstract

In this study, the energy and exergy analysis of Garri 4 power plant in Sudan is presented. The primary objective of this paper is to identify the major source of irreversibilities in the cycle. The equipment of the power plant has been analyzed individually. Values regarding heat loss and exergy destruction have been presented for each equipment. The results confirmed that the condenser was the main source for energy loss (about 67%), while exergy analysis revealed that the boiler contributed to the largest percentage of exergy destruction (about 84.36%) which can be reduced by preheating the inlet water to a sufficient temperature and controlling air to fuel ratio.

Keywords: Exergy, Energy, Steam Power Plant, SDG7

1. Introduction

The energy demand is expected to rise 58% from 2001 to 2025 [1] and due to the high prices of energy and the decreasing fossil fuel resources, the optimum application of energy and the energy consumption management methods are so crucial.

In many countries, steam power plant cycles have been discarded from the power generation cycle due to their low efficiency, environmental pollution, and especially insufficient fossil fuel resources, and have been replaced by power plants with high efficiency and economical and technical justification. Analysis of power generation systems is of scientific interest and also essential for the efficient utilization of energy resources. The most commonly used method for the 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 to evaluate the efficiency with which the available energy is consumed.

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Exergy analysis based on the first and second thermodynamics laws is a significant tool to analyze energy systems. It also reveals the inefficient thermodynamics processes. Recently, exergy analysis has become a key issue in providing a better understanding of the processes, quantifying sources of inefficiency, and distinguishing the quality of energy consumption. Many researchers have recommended that exergy analysis be used to assist decision-making regarding the allocation of resources (capital, research, and development effort, life cycle analysis, etc.) in place of or in addition to energy analysis. Sudan is an agricultural country with fertile land, plenty of water resources, livestock, and forestry resources electricity is one of the key factors for the development of the national economy in Sudan. The available electricity from thermal power plants is 10654 GWh [2]. In 2019 the actual generation from Thermal power plants was 5760.32 GWh which forms 54 % of the available capacity.

Nomenclature	Greek symbols
h specific enthalpy (J/kg)	η_1 energy efficiency
I exergy destruction rate (W)	η_2 exergy low efficiency
m mass flow rate (kg/s)	W specific exergy (J/kg)
P pressure (Pa)	ψ_f exergy factor
Q heat transfer rate to the system (W)	LHV low heating value
s specific entropy (J/kg K)	Subscripts
T temperature (K)	e exit
W work rate or power done by the system (W)	i inlet
X total exergy rate (W)	s isentropic
	f fuel
	el electrical

Garri 4 is one of the thermal power plants connected to the National grid with an installed capacity of 110 MW (6.9 %) of the total thermal electricity production in the country. Various researchers studied exergy analysis for different fired thermal power plants. Aljundi [3] presented energy and exergy analysis of Al-Hussein power plant in Jordan and achieved that Energy losses mainly occurred in the condenser. The percentage ratio of the exergy destruction to the total exergy destruction was found to be maximum in the boiler system followed by the turbine. Ahmadi and Toghraie [4] investigated the steam cycle of Shahid Montazeri Power Plant of Isfahan with an individual unit capacity of 200 MW. Using mass, energy, and exergy balance equations. They found from the energy analysis that 69.8% of the total lost energy in the cycle occurs in the condenser as the main equipment wasting energy, while exergy Analysis Introduces the boiler as the main equipment wasting exergy where 85.66% of the total exergy entering the cycle is lost.

Mahmud et al. [5] Conducted exergy analysis in one unit of a heat coal-fired power plant in Central Queen's land, Australia as a case study. They found the major contributor in exergy destruction is the boiler which accounts for 81% of total exergy destroyed in the power plant, followed by the turbine where about 10% of the exergy is destroyed.

Anjali and Kalivarathan [6] did a comparison of energy and exergy analysis of thermal power plants stimulated by coal. Mangal and Suman [7] did energy and exergy analysis of a thermal power plant at two different loads i.e. 100% and 70% load. Their analysis shows that at design load maximum amount of exergy destruction occurs in the boiler, which is around 42% of the total exergy produced by the burning of coal and maximum energy loss occurs in the condenser which is 68.79%. The comparison of the performance of the Plant is done at design and off-design load and it is found out that plant performance is better at design load than its performance at off-design load. The exergy destruction in the boiler increases to 59% at off-design load. The exergy efficiency of the boiler is significantly reduced at off-design load than any other component of a thermal power plant like a turbine; boiler feed pump, heaters, etc.

Ray et al [8] conducted an Exergy analysis of a 500 MW steam turbine cycle of an operating power plant under the design and off-design conditions with different degrees of superheating and reheat sprays for proper O&M decisions in a steam power plant. Suresh et al. [9] Analyzed the thermodynamic performance of an existing 62.5MW_{el} conventional Rankine cycle power plant using pulverized coal firing. Kaushik et al [10] did a comparison of energy and exergy analyses of thermal power plants stimulated by coal and gas. Regulagadda et al [11] did a thermodynamic analysis of a subcritical boiler turbine generator for a 32 MW coal-fired power plant. A parametric study is conducted for the plant under various operating conditions, including different operating pressures, temperatures, and flow rates, to determine the parameters that maximize plant performance. The exergy loss distribution indicates that boiler and turbine irreversibilities yield the highest exergy losses in the power plant.

Elhelw et al [12] presented the exergy analysis for a 650 MW thermal power plant. At two different loads also the effect of decreasing the condenser pressure, IPT (intermediate pressure turbine) inlet pressure, and increasing S/H (superheating) steam temperature inlet to both HPT (high-pressure turbine) and IPT (intermediate pressure turbine) is studied. The exergy analysis shows that the maximum source of exergy destruction is the boiler, followed by the turbine, then the condenser.

Abuelnuor et al [1] has carried out exergy analysis for Garri2 the results affirmed that thermal and exergetic efficiencies for the entire plant are (38%, 49%) respectively. Emin Açıkkalp et al [13] did a novel combined extended-advanced exergy analysis method for assessing thermodynamic systems.

Robert J. Stakenborghs, Lindsey L. Dziuba [14] presents a description of the various impacts of removing feedwater heaters from service during operation. L A Mondragón et al [15] studied the effect of regeneration on Rankine cycle efficiency. Rosen and Tang [16] investigated the impact of several measures to improve efficiency, primarily developed, based on exergy analysis. The modifications considered here, which increase efficiency by reducing the irreversibility rate in the steam generator.

The major objectives of this study are to evaluate the performance of Garri 4 power plant from a thermodynamics (energy and exergy efficiencies) point of view and to identify the major source of irreversibilities in the cycle and the role of regeneration. Also, this paper reviews the research works which used exergy analysis to study the performance of other power plants.

Figure 1 Schematic diagram of the power plant

2. Plant description

Garri 4 Power Plant Project is fired by Sponge Coke, which is a by-product of the Khartoum Refinery. the refinery is expected to produce a sponge coke amount of approx. 256,100 tons in total per year.

The station operates on the regenerative Rankine cycle. The steam is produced by burning sponge coke produced by the Khartoum refinery in the boiler and the heat is transferred to the fed water through the pipes. The water is converted into steam in the boiler and then gets superheated in the superheater.

The high pressure and high-temperature steam then run through the main steam line to the turbine which consists of 17 stages of fixed and moving blades. After the steam is expanded in the turbine it enters the condenser, the condenser cools down the steam and converts it to what is called condensed water. The condensed water pump pumps it through three heaters called low-pressure heaters where the temperature of the condensed water is raised by the steam bled from the turbine. After that, the water arrives in the Deaerator which is a device that removes oxygen and other dissolved gases from water. Then the water is pumped by the feedwater pumps through two heaters called high-pressure heaters to raise its temperature and then to the boiler and this is how the cycle works as shown in Figure 1.

Table 1 Sponge coke of Khartoum Refinery analysis.

Item	Percentage (%)
Carbon	82.01
Hydrogen	3.25
Oxygen	1.85
Nitrogen	1.66
Sulphur	3
Ash	2.23
Moisture	6

Table 2: Operating conditions of the power plant at 34 MW

Operation Condition	Value
Mass flow rate of fuel	14.7 ton/h
Stack gas temperature	110°C
Feedwater inlet temperature to boiler	156°C
Steam flow rate	39.5 kg/s
Steam temperature	533°C
Steam pressure	7.18 MPa
Power output	34 MW _{el}
Net power output	30 MW _{el}
Fuel exergy	135.57 MW
Heat input	142.059 MW

Table 3 :Exergy destruction

Unit	Exergy destruction rate	Exergy efficiency
Boiler	$I_{boiler} = \dot{X}_{fuel} + \dot{X}_{in} - \dot{X}_{out}$	$n_{2,boiler} = \frac{\dot{X}_{out} - \dot{X}_{in}}{\dot{X}_{fuel}}$
Pumps	$\dot{I}_{pump} = \dot{X}_{in} - \dot{X}_{out} + W_{pump}$	$n_{2,pump} = 1 - \frac{\dot{I}_{pump}}{\dot{W}_{pump}}$
heaters	$\dot{I}_{heaters} = \dot{X}_{in} - \dot{X}_{out}$	$n_{2,heaters} = 1 - \frac{\dot{I}_{heaters}}{\dot{X}_{in}}$
Turbine	$\dot{I}_{turbine} = \dot{X}_{in} - \dot{X}_{out} - W_{turbine}$	$n_{2,turbine} = 1 - \frac{\dot{I}_{turbine}}{\dot{X}_{in} - \dot{X}_{out}}$
Condenser	$\dot{I}_{condenser} = \dot{X}_{in} - \dot{X}_{out}$	$n_{2,condenser} = \frac{\dot{X}_{out}}{\dot{X}_{in}}$
Cycle	$\dot{I}_{cycle} = \sum allcomponent \dot{I}_i$	$n_{2,cycle} = \frac{\dot{W}_{netout}}{\dot{X}_{fuel}}$

3. Analysis

The primary objective of this study is to analyze the power plant components separately and to identify and 15 quantify the sites having the largest energy and exergy losses. To analyze energy and exergy in the water steam heat cycle of the power plant, thermodynamic parameters required for all cycle points shown in figure 1 are extracted from the central control room (CCR) and the flow rate of steam for each equipment is determined applying conservation of mass. Energy and exergy for each equipment are then determined in terms of energy and exergy efficiency and values of unknown parameters are obtained as well using thermodynamic laws. Mass, energy, and exergy balances for any control volume at a steady state with negligible potential and kinetic energy changes can be expressed, respectively, by the Continuity equation:

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

The steady flow energy equation:

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

The steady flow exergy equation:

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

the specific exergy is given by

$$\Psi = h - h_o - T_o (s - s_o) \quad \text{Eq(4)}$$

the total exergy rate is given by

$$\dot{X} = \dot{m} \psi = \dot{m} [h - h_o - T_o (s - s_o)] \quad \text{Eq(5)}$$

The heat supplied to the boiler

$$q_{in} = h_{14} - h_{13} \quad \text{Eq (6)}$$

Fuel exergy

$$\text{Fuel exergy} = \gamma f^* \dot{m}_f * \text{LHV} \quad \text{Eq(7)}$$

Table 4: Energy balance of the power plant components and percent ratio at 34 MW.

Component	Heat Loss (kW)	Percent ratio (%)
Boiler	30464.99	29.1
Turbine	3506.8	3.3
Condenser	70117	67
Generator	623.22	0.6
Total	104712	100.00

The high-pressure heaters were off at the time of the study.

Table 5: Exergy analysis of the power plant

Points	T(°C)	P(MPa)	M(kg/s)	H(kJ/kg)	s(kJ/kg.K)	Ψ	Ẋ(MW)
1	42.6	0.0085	32.418	2458.2	7.82	131.6	4.27
2	42.6	0.0085	37.9	178.41	0.607	2.5	0.10
3	42.64	1.3	37.9	179.71	0.607	3.8	0.15
4	50	1.3	37.9	209.9	0.703	4.43	0.17
5	64.0	0.0283	5.482	267.9	0.877408	9.7	0.05
8	85	1.3	37.9	356.478	1.13387	23.5	0.89
9	127.4	1.3	37.9	535.503	1.60623	61.7	2.34
10	151	0.609	39.5	636.055	1.852	89.0	3.52
11	152.01	11.1	39.5	647.51	1.851	100.7	3.98
13	156	8.1	39.5	662.151	1.89068	103.6	4.09
14	533	7.3	39.5	3487.32	6.87853	1441.6	56.94
17	271	0.609	1.6	3000.91	7.26213	840.8	1.35
18	187	0.252	2.94	2841.45	7.34922	655.4	1.93
19	94	0.077	2.242	2666.81	7.48414	440.5	0.99
20	84	0.0283	0.3	2654.35	7.96443	284.9	0.09
23	127.1	0.252	2.94	533.48	1.60399	60.4	0.18
24	87	0.077	5.182	380.292	1.20334	26.6	0.14
27	90.8945	0.077	2.94	533.48	1.62424	54.3	0.16
28	63.6803	0.0283	5.182	380.292	1.21907	21.9	0.11
29	42.6	0.0085	5.482	267.9	0.885	8.1	0.04

Table 6: Exergy destruction of the power plant component .

Units	Exergy destruction (MW)	Percent exergy destruction (%)
Boiler	82.720	84.36
Turbine	10.200	10.41
Condenser	4.210	4.29
Deaerator	0.170	0.17
HTR4	0.300	0.31
HTR5	0.320	0.33
HTR6	0.080	0.08
Pump1	0.001	0.00
Pump3	0.040	0.04

4. Results and Discussion

The energy balance of the power plant is presented in Table 4. It shows that the thermal efficiency is (21.12%). The energy balance also reveals that 67% of the fuel energy is lost in the condenser and carried out into the environment, while only 29.1% is lost in the boiler. but efficiencies based on energy can often be non-intuitive or even misleading [3]. One of the most important results, is that the maximum destruction was found in the boiler followed by the turbine this finding is in agreement with [3]-[6] also [12] and [16] reached the same results.

Exergy and percent of exergy destruction are summarized in Table 4 for all components present in the power plant. The boiler with 82.72 MW inlet fuel exergy loss covers 84.36% of the total lost exergy, while the condenser with 4.21 MW lost exergy has only 4.29% of the total lost exergy.

According to the first law analysis, energy losses associated with the condenser are significant because they represent about 67% of the energy input to the plant. An exergy analysis, however, showed that only 4.29% of the exergy was lost in the condenser. The real loss is primarily back in the boiler where entropy was produced. This shows that the main contributor of irreversibilities in the cycle is the boiler.

Figure 2 comparisons between heat loss and exergy destruction for the main equipment.

Figure 3 Variations of the pressure in the condenser against turbine work.

Figure 4 Variations of the pressure in the condenser against thermal efficiency.

Figure 5 Effect of the outlet steam temperature on turbine work.

Figure 6 Effect of feed water temperature on thermal efficiency

Fig 2 shows a comparison between heat loss and exergy destruction for the main component in the power plant. The energy balance also shows that the condenser contributed to the largest heat loss in the plant, while only 29.1% of heat was lost in the boiler. Although losses of energy can be large quantity while it is thermodynamically insignificant. Fig 3 shows the variations of the load against pressure variation in the condenser. As can be seen, condenser pressure has a significant impact on the load produced by the turbine it is seen that for approximately every 0.08 MPa reduction in the condenser pressure is associated with a 2 MW increase in the output load Similarly P. Regulagadda, I. Dincer, G.F. Naterer [11] found every 0.08 reduction in the condenser is associated with 3.6 MW increase in the output load. As it is specified by increasing the condenser pressure from 0.02 MPa to 0.1 MPa the load unit reduced from 33.25 to 31.12 MW. The pressure of the condenser rises due to a poor vacuum. Also, the smaller the cooling water flow rate for a given cooling water inlet temperature, the higher will be the condenser pressure. When the cooling water temperature increases, the condenser pressure increases. Cooling water temperature may vary as the season change in a year and hence its mass flow rate should be varied to maintain the condenser set pressure to get the optimum cycle efficiency and power output.

Fig 4 shows the changes in the thermal efficiency of the cycle following the condenser pressure changes can be observed lowering the condenser pressure from 0.1 to 0.02 MPa increases the efficiency from 22.04 to 23.56 %. As the condenser pressure has a large effect on turbine efficiency and finally on production increase, every step toward reducing the condenser pressure will be effective.

Fig 5 shows that approximately every 5°C increase in the outlet steam temperature is associated with a 0.575 MW increase in the load output. This close to Ahmadi [4] finding which showed that every 5 °C in the main steam temperature is associated with a 0.68 MW increase in the load output and with 0.34% efficiency increase this the same finding of P. Regulagadda, I. Dincer, and G.F. Naterer [11].

Fig 6 shows the effect of the inlet water temperature on thermal efficiency; a higher feedwater temperature increases the mean temperature of heat addition from the flue gas to the steam cycle. The thermal efficiency of the Rankine cycle increases when the average temperature of heat addition is higher. High feedwater temperature is normally achieved by regenerative pre-heating. Garri 4 High-pressure heaters are out of service due to valve defects, this reduces the inlet feed water temperature which lowers the efficiency of the station which led to high consumption of fuel which resulted in higher expenditure. 18.76 % reduction in the heat rate was calculated if the heaters were in service for the same conditions.

5. Conclusion

The energy balance of the power plant shows that the thermal efficiency to be 21.12%. The condenser heat lost accounted for 67% while the boiler accounted for 29.1%. Although losses of energy can be large quantity while it is thermodynamically insignificant. The calculated exergy efficiency of the power cycle was 22.1%, which is low compared to modern power plants. The Exergy destruction rate of the boiler (where entropy was produced) is dominant over all other irreversibilities in the cycle; it counts alone for 82.72% of the plant while the condenser destruction losses are only 4.21%.

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