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On the Energy and Exergy Analysis of a 500 Kw Steam Power Plant at Benso Oil Palm Plantation (BOPP)

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Abstract

Thermodynamic systems are analysed using two essential tools (The Energy and Exergy Analysis). However, system analysis based on the energy law (quantity) alone is deceptive, because the exergy law shows that energy has quantity as well as quality. The normal energy analysis evaluates the energy on its quantity only. The aim of this study is to use energy and exergy analysis to identify the locations and magnitudes of losses in order to maximise the performance of a 500 KW open system steam power plant at BOPP. The required outputs (work, heat and irreversibility) of the various components are assessed and calculated using mass, energy and exergy balance equations. The results indicate that about 50 % of heat energy generated in the combustor is destroyed. In conclusion, further improvement in the combustor will maximize the plant performance hence the results show how energy and exergy have been used to locate places of inefficiencies in the plant.

Keywords: Benso Oil Palm Plantation (BOPP), Exergy, Energy, Thermodynamic Analysis, Irreversibility, Exergy loss, Systems

1 Introduction

The increased awareness that the world's energy resources are limited has caused many countries to re-examine their energy policies and take drastic measures in eliminating waste. It has also sparked interest in the scientific community to take a closer look at the energy conversion devices and to develop new techniques to better utilize the existing limited resources (Cengel and Boles, 2008).

Nowadays, there are a few methods to measure the performance of a power plant (Hussein *et al*, 2001). The first law of thermodynamics (Energy analysis) deals with the quantity of energy and asserts that energy cannot be created or destroyed. The law merely serves as a necessary tool for the bookkeeping of energy during a process and offers no challenges to the engineer. The second law (Exergy analysis), however, deals with the quality of energy. It is concerned with the degradation of energy during a process, the entropy generation, and the lost opportunities to do work; and it offers plenty of room for improvement. The second law of thermodynamics has proved to be a powerful tool in the optimization of complex thermodynamic systems (Ganapathy *et al*, 2009; Makinde, 2007; Cengel and Boles, 2008). In recent times, exergy analysis has become a key aspect in providing a better understanding for the analysis of power system processes, the quantification of sources of inefficiencies and distinguishing quality of energy (or heat) used (Jin *et al*., 1997; Gong and Wall, 1997; Rosen and Dincer, 1997).

Energy is always conserved (in balance); it can neither be produced nor consumed. Exergy is only conserved or in balance for a reversible process, but partly consumed in an irreversible process (real processes). Thus, exergy is never in balance for real processes. Energy is a measure of quantity. Exergy is a measure of quality and quantity. For a real process, the exergy input always exceeds the exergy output; this imbalance is due to irreversibilities which we name exergy destruction. The exergy output consists of utilized output and non-utilized output (Dincer and Al-Muslim, 2001).

Although the method of exergy is often considered to be a new method for analyzing energy systems, the underlying fundamentals were introduced as early as in the 1940's (Hussein *et al*, 2001). For example, exergy evaluation was applied to a supercritical steam turbine, which revealed that high losses occurred in the heat recovery steam generator and turbine thus, the system was improved (Jin *et al*, 1997). Also, in a plant facility of which 77 MW of fuel and 2.2 MW of power were needed, by exergy analysis it led to a great reduction in power cost and the fuel consumption was cut down to a value between 45 and 60 MW (*Gaggioli et al*, 1991).

2 Materials and Methods

Study Area

Benso Oil Palm Plantation (BOPP) is a limited liability company which commenced operation in 1976 as a joint venture between United African Company (U.A.C) and Ghana government. The government shares were divested to the public in 2004 and the company got listed on the Ghana Stock Exchange with Unilever Ghana as the majority share holder and having management control. BOPP is one of the largest producers of palm oil in Ghana. The plantation is 42 km from Takoradi, which is Ghana's second port city and capital of the Western Region and it's also about 267 km from Accra, Ghana's capital City and about 297 km from Tema the first port city of Ghana. BOPP is also accessible by rail and is next to the Benso Railway Station on the Takoradi to Tarkwa line. Currently, there are 3,866 hectares of mature oil palms which were planted between 1978 and 2004. The company has an office in Accra which handles shipping, supplies and other business.

As in many organisational setups involving production, the scheduled working time contribute to the productive capacity of the company. It is important therefore to ensure that equipment usage is maximised to save time and money. Again, production managers are demanding strict guaranteed performance to meet production targets. Continuous power supply is necessary for the achievement of these targets. In Ghana, power supply to many consumers has over the years been done by the Electricity Company of Ghana (ECG) but this supply has always not been reliable, with its many power outages.

Due to the unreliability of power supply from ECG, BOPP management established a steam power plant to supplement power supply from ECG using fibre and shell as the fuel for firing the boiler. The plant produces electrical power by using the energy released from the steam generated in the boiler to drive the turbine blades which in turn drives a generator to generate the needed power. The installed plant is to generate power for the processing of oil palm and palm kernel as well as to supply power for the effluent pond operations and water supply installations. The designed power output of the generator is 500 kW (Nadrowski, 1992) but due to operational inefficiencies and other losses, the daily output is between 350 – 400 kW. This research seeks to investigate the causes of operational inefficiencies and losses using energy and exergy analysis.

Analysis of the Plant

The cycle with superheat is used for this analysis. At the plant site, a separate tubing system known as the superheater is placed in the combustion gas chamber. Fig.1 shows a schematic representation of the cycle with superheat. Generally, water flows from the feed pump to the steam drum to be heated. The superheated steam enters the turbine and after generating the necessary power it exist the turbine for use in other heating processes or blown into the atmosphere. The water in the boiler drum is heated by the furnace gases to generate saturated steam. The saturated steam then passes from the top of the boiler drum, through the nest of superheated tubes and return to the main stop valve. Superheated steam is drawn off to the turbine where it expands, doing work on the blades of the turbine which drive the electrical generator. After expansion through the turbine, the steam exit still superheated and then used for processes such as fruit sterilization

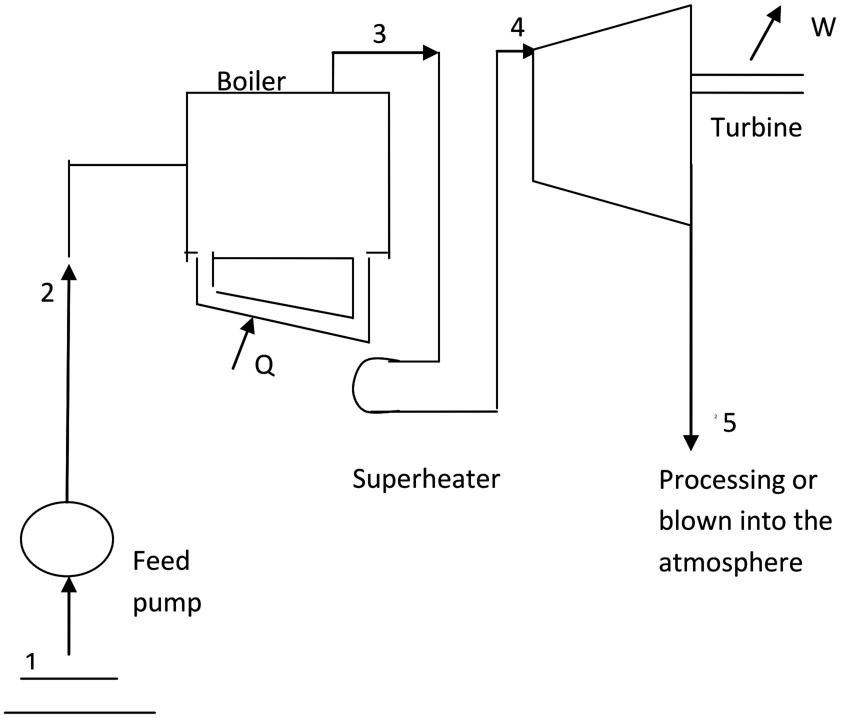

Fig. 1 Schematic Representation of the Cycle with Superheat

Considering the individual components of the diagram in Fig.1, the three balance equations are applied to find the work output, the heat added and the rate of irreversibility. The balance equations are then written as (Dincer and AL-Muslim, 2000; Cengel and Boles, 2008; Ganapathy *et al*, 2009):

The mass balance equation:

$$\sum_{i=1}^{n=\infty} \dot{m}_i = \sum_{e=1}^{n=\infty} \dot{m}_e \tag{1}$$

The energy balance equation:

$$\sum_{i=1}^{n=\infty} E_i + \dot{Q}_{cv} = \sum_{i=1}^{n=\infty} \dot{m}_i + \dot{W}_{cv} \tag{2}$$

The exergy balance equation:

$$\sum_{i=1}^{n=\infty} {}_i A_i + \sum {}_i \left(1 - \left[\frac{T_0}{T_j}\right]\right) \dot{Q}_{cv} = \sum_{e=1}^{n=\infty} {}_e A_e + \dot{W}_{cv} + I \tag{3}$$

Where

i - inlet of a component

e - exit of a component

$\dot{m}$ - mass flow rate

A - exergy

$\dot{W}_{cv}$ - work rate in a control volume

$\dot{Q}_{cv}$ - heat transfer rate in a control volume

T_o - surrounding temperature and reference temperature

T_j - temperature of system

I - irreversibility or exery loss

Feed Pump

The balanced equations for mass, energy and exergy used in finding the energy and exergy losses in the feed pump (Fig. 2) are given in equations 4, 5 and 6 (Dincer and AL-Muslim, 2000; Cengel and Boles, 2008; Ganapathy *et al*, 2009).

$$\dot{m}_{fpi} = \dot{m}_{fpe} \tag{4}$$

$$\dot{m}_{fpi}(h_{fpi} - h_{fpe}) + \dot{W}_{FP} = \dot{Q}_{FP} \tag{5}$$

$$\dot{m}_{fpi}(\varepsilon_{fpi} - \varepsilon_{fpe}) + \dot{W}_{FP} = \dot{I}_{FP} \tag{6}$$

where

ε_{fpi} - specific exergy at feed pump inlet

ε_{fpe} - specific exergy at feed pump exit

h_{fpi} - specific enthalpy at feed pump inlet

h_{fpe} - specific enthalpy at feed pump exit

$\dot{W}_{FP}$ - work transfer in feed pump

$\dot{Q}_{FP}$ - heat transfer loss in feed pump

$\dot{I}_{FP}$ - exergy loss in feed pump

fpi - feed pump inlet

fpe - feed pump exit

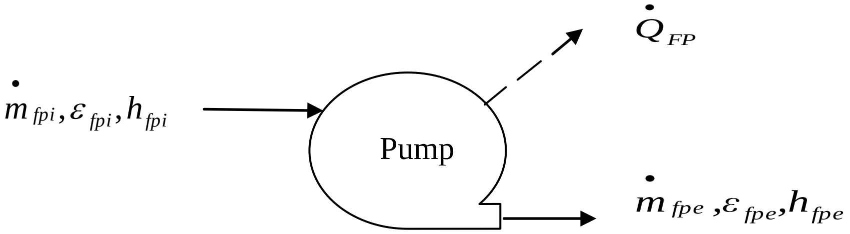

Fig. 2 Energy and Exergy Balances for Feed Pump

Boiler

The energy losses, $\dot{Q}$, of the boiler components are determined using the energy balance equation and the exergy losses, $\dot{I}$, are calculated from the exergy balance equations.

Combustor

The mass, energy and exergy balance equations of a combustor see Fig. 3 (Ganapathy *et al*, 2009) are:

$$\dot{m}_f + \dot{m}_a = \dot{m}_g \tag{7}$$

$$\dot{m}_f\left(h_f - h_g\right) + \dot{m}_a\left(h_a - h_g\right) = \dot{Q}_C \tag{8}$$

$$\dot{m}_f\left(\varepsilon_f - \varepsilon_g\right) + \dot{m}_a\left(\varepsilon_a - \varepsilon_g\right) - \dot{E}_{QC} = \dot{I}_c \tag{9}$$

Where

f - fuel

a - *air*

g - *gas*

c - combustor

All other parameters have their usual meanings defined above

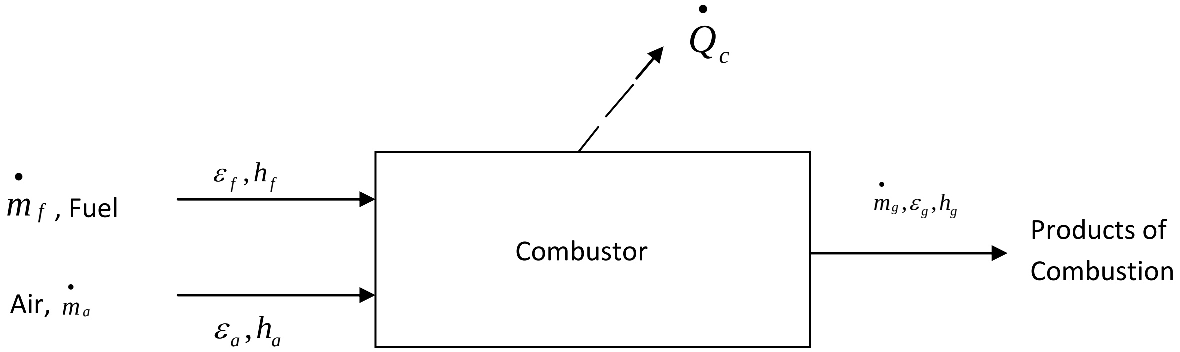

Fig. 3 Energy and Exergy Balances for Combustor

Superheater

A diagram of the superheater showing the enegy and exergy balances of the system are shown in Fig. 4

Mass balance for the gas side:

$$\dot{m}_{giSH} = \dot{m}_{goSH} = \dot{m}_g \tag{10}$$

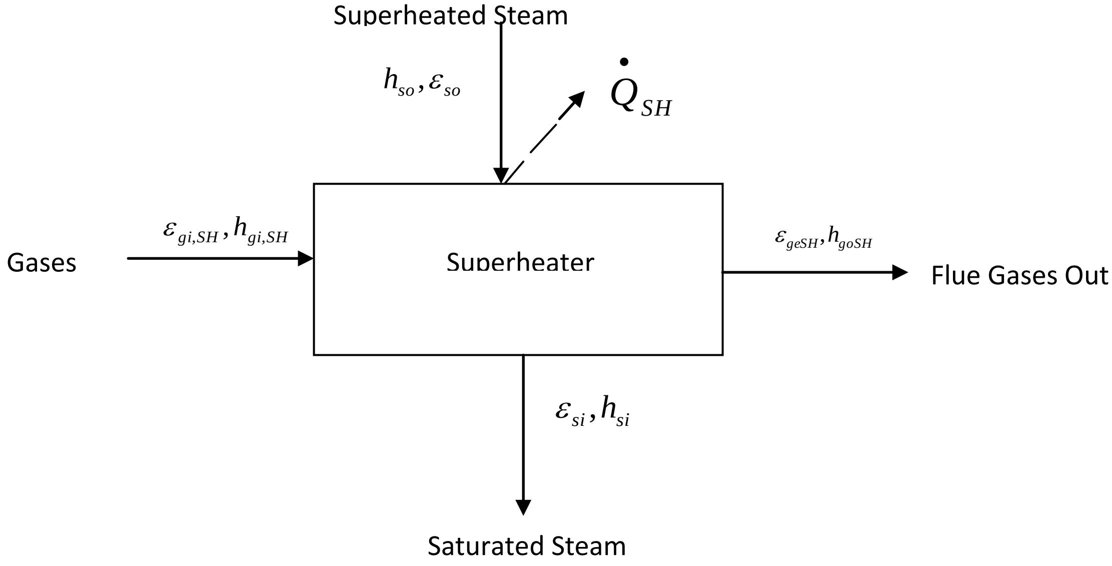

Fig. 4 Energy and Exergy Balances for Superheater

Mass balance for the steam side

$$\dot{m}_{si} = \dot{m}_{so} = \dot{m}_s \tag{11}$$

Energy balance:

$$\dot{m}_g \left(h_{giSH} - h_{goSH}\right) + \dot{m}_s \left(h_{si} - h_{so}\right) = \dot{Q}_{SH} \tag{12}$$

Exergy balance:

$$\dot{m}_g\left(\varepsilon_{giSH}-\varepsilon_{goSH}\right)+\dot{m}_s\left(\varepsilon_{si}-\varepsilon_{so}\right)-\dot{E}_{Q_{SH}}=\dot{I}_{SH} \tag{13}$$

Where

si - inlet steam

so - outlet steam

SH - superhearter

$\dot{E}_{Q_{SH}}$ - exergy due to heat transfer loss in the superhearter

Steam Turbine

The equations of energy and exergy balances are used to calculate the energy losses and exergy destructions in the turbine. The mass, energy and exergy balances for the steam turbine are given in equations 14, 15 and 16.

$$\dot{m}_{si}=\dot{m}_{so}=\dot{m}_s \tag{14}$$

$$\dot{m}_s\left(h_{si}-h_{so}\right)-\dot{W}_T=\dot{Q}_T \tag{15}$$

$$\dot{m}_s\left(\varepsilon_{si}-\varepsilon_{so}\right)-\dot{W}_T-\dot{E}_{Q_T}=\dot{I}_T \tag{16}$$

Where

$\dot{E}_{Q_T}$ - exergy due to heat transfer loss in turbine

T - turbine

Discussions and Analysis of Results

The actual operating data of the components such as, feed water pump temperature and pressure, boiler temperature and pressure, mass flow rates of fuel and steam and turbine inlet and outlet conditions of the 500 kW steam plant at BOPP were collected for the analysis to calculate the enthalpies and exergies at different state points of the plant. The important process data for the plant unit is summarized in Table 1. Also, the energy and exergy losses of these components have been determined using the equations given in the previous section.

Table 1 Important Process Data for the Plant Unit

COMPONENT	Temperature (^{o} C)	Pressure (bar)
Feed Water Pump Inlet	90	0.7
Feed Water Pump Inlet	110	1.4
Turbine Inlet	300	17
Turbine Outlet	180	3
Reference or Surrounding Conditions	32	1.13
Flue Gas Inlet Condition	600	
Flue Gas Outlet Condition	350	
Mass Flow Rate of Steam - 2.5 kg/sec Mass Flow Rate of Fuel (Fiber) - 2.0 kg/sec		

From the exergy analysis, it was deduced that the feed water pump has no wasted work potential but looking at the boiler section (i.e. combustor and superheater) with a greater amount of heat generated in the chamber some is not available for doing any work. Thus the First law analysis (Energy analysis) as shown in Fig. 5 gave only the quantity of heat generated in the combustion chamber and divert our attention on the improvement of the plant performance. Hence the First law analysis cannot be used to pinpoint prospective areas for improving the plant performance.

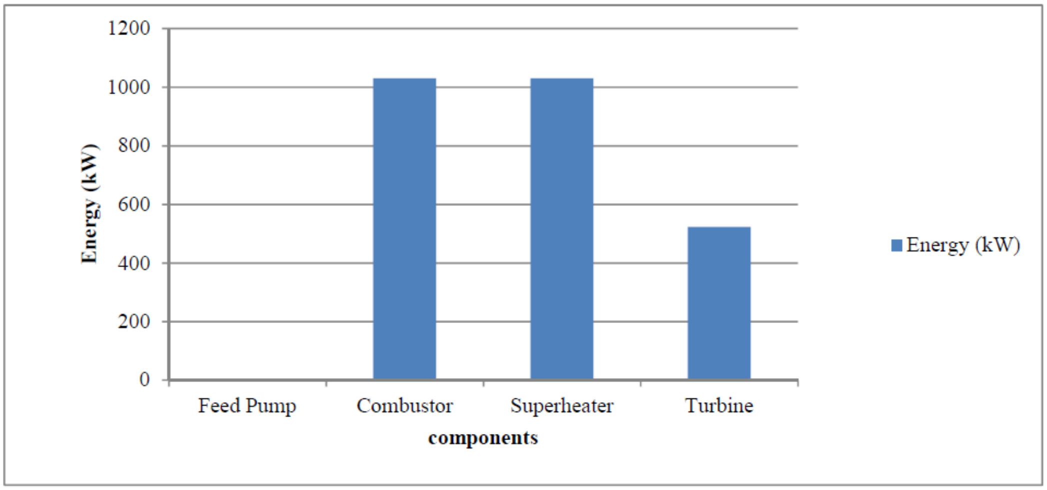

Fig.5 Component versus Energy Output

Moreover, with the Second law analysis (exergy analysis) the higher irreversibility in the combustor and superheater as shown in Fig. 6 is partly due to less heat energy delivered to the superheater tubes. Hence with an increase in the heat energy supply the work output of the turbine will be higher and the irreversibility reduced to the minimal.

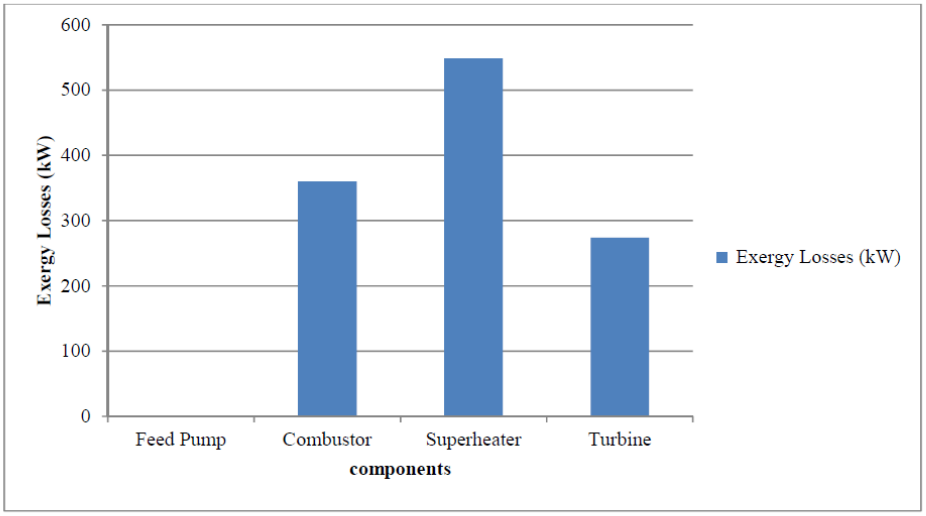

Fig. 6 Component versus Exergy Losses

The First law analysis (energy analysis) pinpoints that the amount of energy which is available in the combustor for useful work is higher thus with an improvement in this section, the plant performance will increase coupled with a maximum work output from the turbine. The combined graphs of the energy and exergy losses are shown in Fig. 7. Also, the smaller the irreversibility associated with a process (i.e. the feed water pump), the greater the power that is produced or the lesser the power consumed; therefore, the performance of a system can be improved by minimizing the irreversibility associated with it.

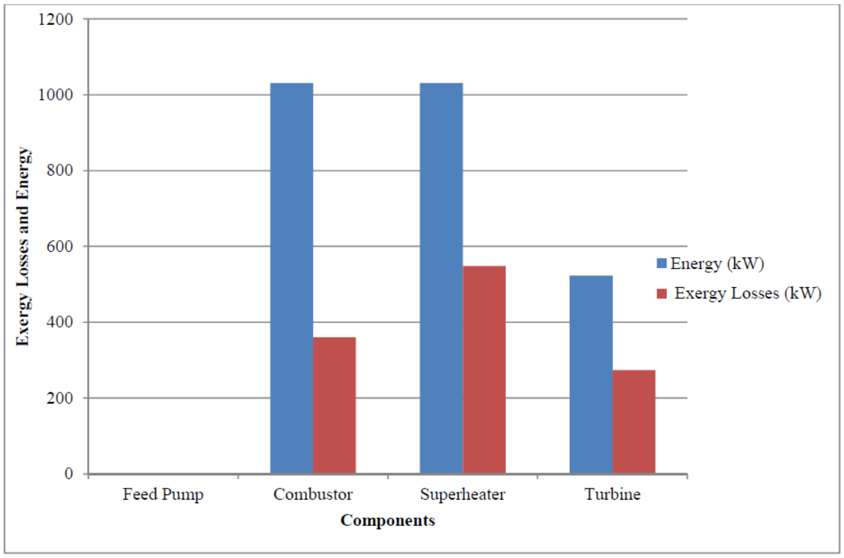

Fig. 7 Combined Graphs of Exergy Losses and Energy Output versus Components

Conclusion

An energy and exergy analysis was performed on a steam plant of 500 kW output at BOPP and the energy, exergies and loss opportunity to do work have been determined for the various components considered. The results indicate that about fifty percent (50 %) of the total heat energy generated in the combustion chamber is not available for doing any useful work thus having its effect on the work output of the turbine. This is due to the irreversibility inherent in the combustion process and the inability to de-ash the chamber at the required time thus preventing smooth circulation of the flue gases on the water tubes. Hence the exergy analysis pinpoints the system where attention has to be paid to maximize the plants performance.

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