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EXERGY ANALYSIS OF A STEAM POWER SYSTEM FOR POWER PRODUCTION

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ABSTRACT
The present study deals with an 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. Therefore, the effect of key parameters on the output power and efficiency are so important. In this paper, the effects of key parameters in both firs law and second law of thermodynamics point of view have performed. It was intended to determine unfavorable points from exergy destruction concept using exergy analysis for steam power plants cycle. Also, variation in efficiency and exergy destruction is evaluated using variations of temperature of high pressure steam, temperature of reheat, and condenser pressure. The study of the effect of feed-water heaters shows that increase in number of heaters up to 3 causes increase in both first and second low efficiency, but further increase has the reverse effect. The results show that boiler has the greatest exergy destruction among the power plant components.

Keywords: Steam power plant, Exergy analysis, Efficiency, Exergy destruct.

1. INTRODUCTION

Steam power plants are widely utilized throughout the world for electricity generation, and coal is often used to fuel these plants. Although the world's existing coal reserves are sufficient for about two centuries, the technology largely used today to produce electricity from coal causes significant negative environmental impacts. To utilize coal more effectively, efficiently and cleanly in electricity generation processes, efforts are often expended to improve the efficiency and performance of existing plants through modifications and retrofits, and to develop advanced coal utilization technologies.

The general energy supply and environmental situation requires an improved utilization of energy sources. Therefore, the complexity of power-generating units has increased considerably. Plant owners are increasingly demanding a strictly guaranteed performance. This requires thermodynamic calculations of high accuracy. As a result, the expenditure for thermodynamic calculation during design and optimization has grown tremendously. The most commonly-used method for evaluating the efficiency of an energy-conversion process is the first-law analysis. 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 (Dincer and Al-Muslim, 2001). 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. 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 (Habib et al. 1992 and, Ganjeh Kaviri et al. 2012). On the other hand, the low critical temperature of water (which is the most common carrier fluid in steam cycles) and the limited maximum metallurgic temperature which is permitted in the steam power plants have caused the real gas turbine cycles to work at a considerably higher temperature than the steam cycles. The highest carrier fluid temperature at the input of turbine in the steam power plants is around 540-650 ˚C, while the same temperature in the gas turbines amounts to around 1100-1650 ˚C (Roosen et al. 2003). It should be noted that in case a recovery system is used, the optimum pressure ratio, which results in the maximization of thermal efficiency, leans towards smaller values. In the literature, there are papers which have studied the methods for increasing the output power and efficiency of combined cycle. Kotas and Moran (Kotas. 1985, Moran. Et al. 2002) investigated exegy reductions for various systems and also estimated the amount of exergy loss in different systems. Franco & Russo (Franco, Russo. 2002) applied a method to increase the efficiency of a combined cycle power plant by means of exergy analysis based on the optimization of the heat recovery boiler. The main emphasis in this reduction was on the optimization of the recovery boiler. Dincer and Al-Muslim (Dincer and Al-Muslim, 2001) analyzed a Rankine cycle reheat steam power plant to study the energy and exergy efficiencies at different operating conditions with varying boiler temperature, boiler pressure, mass fraction ratio and work output from the cycle. Ganjehkaviri (Ganjeh Kaviri et al. 2012)analyzed multi-objective optimization of a combined cycle power plant the results show that gas turbine temperature, compressor pressure ratio and pinch point temperatures are significant design parameters. It means that any changes in these design parmeters lead to a drastic change in objective functions and also by increasing the temperature of the super heater, both the exergy loss in the heat recovery boiler and the cost of exergy loss are reduced. In recent years a new concept has been introduced by researchers, called exergoeconomic/thermoeconomics, which combines thermodynamics with economics. There are numerous studies about exergoeconomic in the literature done for power plant as well as cogeneration (CHP) plants. Rosen and Dincer (Rosen, Dincer, 2003) performed an exergoeconomic analysis of power plants and applied it on a coal fired electricity generating station. They found that the ratio of thermodynamic loss rate to the capital cost is a significant parameter in evaluating the plant performance, which may lead to a successful trade-off in the design of the plant.

2. EXERGY ANALYSIS

Exergy is composed of two important parts. The first one is the physical exergy and the second one is the chemical exergy. In this study, the kinetic and potential parts of exergy are negligible. The physical exergy is defined as the maximum theoretical useful work obtained as a system interact with an equilibrium state. The chemical exergy is associated with the departure of the chemical composition of a system from its chemical equilibrium. The chemical exergy is an important part of exergy in combustion process. It is important to observe that unlike energy, exergy is exempt from the law of conservation. Irreversibility associated with actual processes cause exergy destruction.

In order to do the exergy analysis, mass and energy balances on the system are required to determine the flow rates and energy transfer rates at the control surface. If one applies the first and second laws of thermodynamics, one can find the formula for exergy balance as the following (Mansouri et al. 2012):

Continuity Equation:

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

Energy Equation:

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

Exergy balance Equation:

$$\dot{E}x_Q + \sum_i \dot{m}_i ex_i = \sum_e \dot{m}_e ex_e + \dot{E}x_W + \dot{E}x_D \quad (3)$$

Where subscripts i and e refer to streams entering and leaving the control region, respectively. $\dot{E}x_D$ is the exergy destruction. The exergy rate of a stream of substance (neglecting the potential and kinetic components) can be written in the form:

$$\dot{E} = \dot{E}_{pH} + \dot{E}_{cH} \quad (4)$$

Where $\dot{E} = \dot{m}e$ The mixture chemical exergy is defined as follows (Ganjeh Kaviri et al. 2012):

$$ex_{mix}^{Ch} = \left[\sum_{i=1}^{n} X_i ex^{Ch_i} + RT_0 \sum_{i=1}^{n} X_i LnX_i + G^E\right] \quad (5)$$

The last term, G^E, which is the excess free Gibbs energy, is negligible at low pressure at a gas mixture. One can generalize the chemical exergy concept of fuel to every $C_\alpha H_\beta N_\gamma O_\delta$ component (Rosen, Dincer, 2003). The molar chemical exergy ex_C^{Ch} of such a component will be:

$$ex_C^{Ch} = \left(\mu_{c,o} - \mu_c^e\right) \quad (6)$$

Where μ_c^e refers to the chemical potential of the component at the restricted dead state.

$$\mu_c^e = \alpha\bar{\mu}_{co_2}^e + \left(\beta/2\right)\bar{\mu}_{H_2o}^e + \left(\gamma/2\right)\bar{\mu}_{N_2}^e + \left(-\alpha - \beta/4 + \delta/2\right)\bar{\mu}_{o_2}^e \quad (7)$$

represents the chemical potential of the components at their thermo-mechanical equilibrium state with the standard ambient.

For the evaluation of the fuel exergy, the above formula cannot be used. Thus, the corresponding ratio of simplified exergy is defined as the following:

$$\xi = {ex_f}/{LHV_f} \quad (8)$$

Due to the fact that for the most of usual gaseous fuels, the ratio of chemical exergy to the Lower Heating Value is usually close to 1, one may write(Ganjeh Kaviri et al. 2012):

$$\xi_{cH_4} = 1.06$$

$$\xi_{H_2} = 0.986 \quad (9)$$

For gaseous fuel with C_xH_y, the following experimental equation is used to calculate ξ:

$$\xi = 1.033 + 0.0169\frac{y}{x} - \frac{0.0698}{x} \quad (10)$$

$$\dot{E}_Q = \left(1 - \frac{T_0}{T_i}\right)\dot{Q}_i \quad (11)$$

$$\dot{E}_W = \dot{W} \quad (12)$$

$$e_{ph} = (h - h_0) - T_0(S - S_0) \quad (13)$$

Where T is the absolute temperature (K) and subscripts (i) and (o) refer to inlet and ambient conditions respectively. In the exergy analysis of power plants, the exergy of steam is calculated at all states and the changes in the exergy are determined for each major component. Unlike energy, exergy is not conserved but destroyed in the system. In the components of the plant exergy is dissipated during a process because of friction, mixing, combustion, heat transfer, etc. The source of exergy destruction (or irreversibility) in boiler and steam turbine is mainly combustion (chemical reaction) and thermal losses in the flow path respectively. However, the exergy destruction in the heat exchangers of the system i.e. condenser, feed water heater, is due to the large temperature difference between the hot and cold fluid.

The objective of present study is to perform an exergy analysis and simulation of steam power plant which is very common cycle to produce power in iran. For this reason after simulation and thermodynamic modeling of this cycle, we calculate exergy balance for each component table (1), and after that the effect of changing in the boiler pressure on the exergy efficiency and exergy destruction of the plant were performed. For having good insight of the concept of exergy analysis for this power plant, the effect of the condenser pressure on the cycle efficiency was performed.

For simulation power plant, a computer simulator is used. In part of this paper the effect of feed-water heaters on thermodynamic performance of power plant is evaluated, in which in any cases modeling and simulation of the cycle is well performed with the simulator.

Table 1: The exergy destruction rate and exergy efficiency equations for plant components

Components	Exergy Destruction	Exergy Efficiency
Boiler	$\dot{E}_{D,B} = \dot{E}_f + \sum_{i,B} \dot{E} - \sum_{e,B} \dot{E}$	$\eta_{e,B} = \left(\dot{E}_{e,B} - \dot{E}_{i,B}\right) / \dot{E}_f$
Steam Turbine	$\dot{E}_{D,T} = \sum_{i,T} \dot{E} - \sum_{e,T} \dot{E} - \dot{W}$	$\eta_{e,T} = \dot{W}_t / \left(\dot{E}_{i,T} - \dot{E}_{e,T}\right)$
Pump	$\dot{E}_{D,P} = \dot{E}_{i,P} - \dot{E}_{E,P} + \dot{W}_P$	$\eta_{e,p} = \left(\dot{E}_{i,p} - \dot{E}_{o,p}\right) / \dot{W}_p$
Heater	$\dot{E}_{D,H} = \sum_{i,H} \dot{E} - \sum_{e,H} \dot{E}$	$\eta_{e,H} = \sum_e \dot{E} / \sum_i \dot{E}$
Condenser	$\dot{E}_{D,C} = \sum_{i,C} \dot{E} - \sum_{e,C} \dot{E}$	$\eta_{e,C} = \dot{E}_{e,C} / \dot{E}_{i,C}$

Table 2 shows the thermodynamic specifications of the specified steam cycle.

Table 2: operating condition of the steam power plant

Element	Unit	Amount
Feed water inlet temperature to boiler	C	261.99
Mass flow rate of high pressure steam	Kg/s	511
High pressure steam temperature	C	544
High pressure of the boiler	bar	143
Reheat mass flow rate	ton/hr	441
Reheat temperature	C	527
Reheat pressure	bar	30
Boiler efficiency	%	97
Output Power	MW	158
Number of Heaters	N	5
Cooling mass flow rate	ton/hr	14470
Boiler feed pump efficiency	%	83

3. RESULT AND DISCUSSION

In the first section of this paper energy destruction analysis is performed for each component of the cycle. According to the obtained results Table 3, it is seen that boiler has the most value of exergy destruction (200 MW), which is 80.3% of the total cycle losses. Also, its exergy efficiency is 56.6%. After that, the condenser is in second place with 32 MW exergy destruction (12.74% of the total losses), and having 56% exergy efficiency. The schematic diagram of a 158 MW steam power plant is shown in Figure 1.

Table 3: calculation of exergy destruction, exergy efficiency and percent exergy destruction

	Exergy destruction (MW)	Percent exergy destruction%	Exergetic efficiency%
Boiler	201.27	81.3	56.6
Condenser	33	13.3	56
Turbine	5.27	2.12	84
feed pump	2.65	1.07	66
Heater1	0.9	0.36	87.5
Heater2	1.19	0.48	89
Heater3	1.1	00.44	85
Dearator	0.4	0.16	0.95
Heater4	2.17	0.87	51
Power cycle	247.55	100	36/5

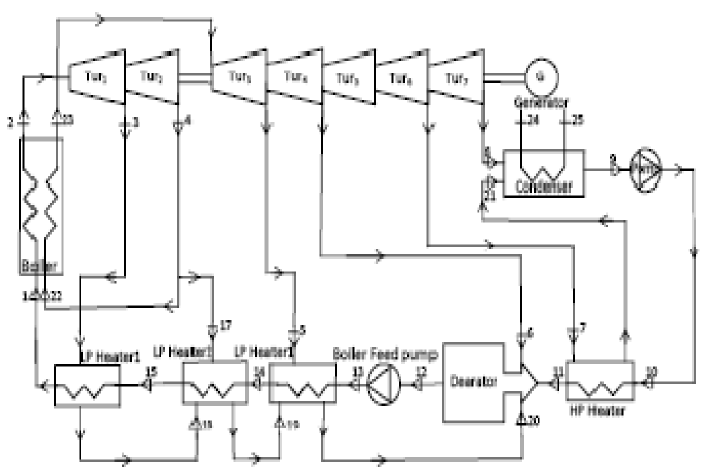

Fig 1: simulation and schematic diagram of a 160 MW steam power plant

It seems that these two components should be in greater point of attention, while performing the optimization of the whole cycle. Another matter is that, since the condenser has the highest value of energy losses, its exergy destruction must has the highest value, too. But, the results of the evaluation show that the rate of irreversibility in boiler is more than other components. And these results indicate that boiler has a greater potential for efficiency optimization. Feed-water heaters that are extracted from the last stages of turbine, since heat transfer occurs in them in lower temperatures, have more exergy destruction, and therefore, have lower exergy efficiencies. The property of each line of this power plant is stated in Table 4.

Table 4: the properties of each line of the power plant

Point	$\dot{m}$(ton/h)	P(bar)	T(^{o}C)	H(kj/kg)	h(kj/kg^{o}C)
1	509	155	251.99	1095.6	294.72
2	509	140	541	3436.9	1555.33
3	26.24	36	446.76	3271	1377.65
4	482.8	36	345.82	3092.3	1184.14
5	20.4	17	443.21	3325.4	1219.44
6	44.93	6	298.05	3058	936.83
7	23.7	2	180.3	2831	693.88
8	352.3	0.1	45.8	2400	219.82
9	376.08	0.09	40.76	170.73	4.398
10	376	6.3	40.86	171.82	5.05
11	376	6.1	80.29	336.65	27.46
12	509	5.9	158.2	667.65	114.62

As is shown in figure (2), when pressure of high pressure line increases, the cycle efficiency increases from 39.5% to 43.5%. as it is shown, since increasing steam pressure requires more input work to the pump, further increase in the pressure to above 160 bar does not a practical increase in exergy efficiency of the cycle.

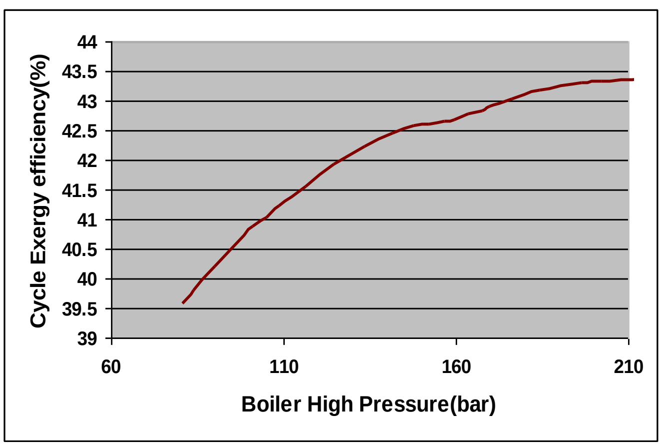

Fig 2: effect of boiler pressure on the cycle exergy efficiency

Also, for condenser pressure (figure (3)), it is seen that increasing pressure causes reduction in overall efficiency of the cycle, due to increase in back-pressure downstream the turbine and irreversibility intensification in turbine. But, because lowering the condenser pressure, to achieve a better vacuum, has both reverse and positive actions on air ejector's steam consumption, this factor should be seen in design, too. It is seen in the modeled cycle that condenser pressure decrement from 0.5 to 0.05 bar causes increase in efficiency from 37.5% to 43%, in which variation range is greater in lower pressures. This indicates that the more pressure reduction in lower pressures, the more increase in cycle efficiency.

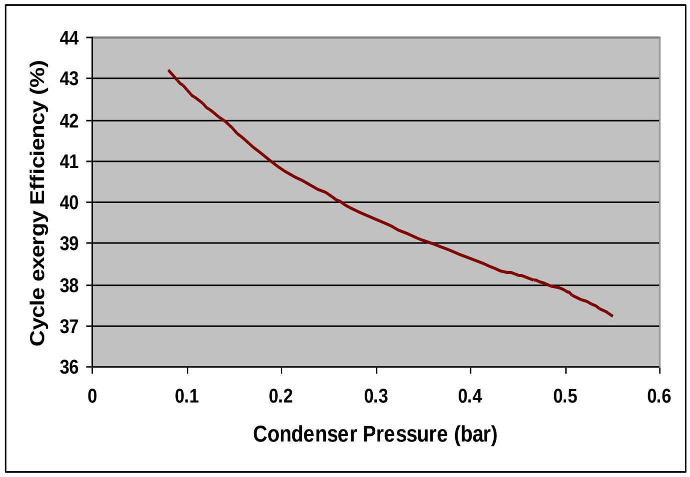

Fig 3: Effect of condenser pressure on the cycle exergy efficiency

Although feed-water heaters increase feed-water temperature, they increase the rate of irreversibility due to exergy destruction that occurs in them. Therefore, using proper number of heaters is in critical importance.

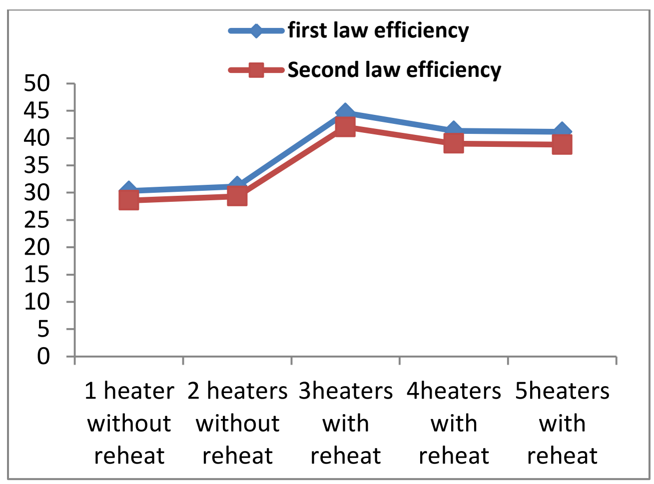

Fig 4: variation of first and second low efficiency Vs Number of heaters

As it is shown in figure (4) the results of study on the number of heaters show that with increasing number of heaters up to 3, second low efficiency increases from 29% to 41%. For increasing number of heaters to 4, there is a sensible reduction in second low efficiency, while further increase does not have significant effect on the efficiency. One should note that large steam power plants require larger number of heaters. But, it is obvious that increasing feed-water heaters up to a certain number causes increase in second low efficiency, while further increase has the reverse

4. CONCLUSION

In this paper, exergy analysis for a simulated cycle of a steam power plant is performed, in which after general analysis of the cycle, the effect of the number of feed-water heaters, condenser pressure, main-steam temperature and pressure, and re-heat temperature e on exergy destruction in major components is studied, too. With overall analysis of the cycle, it is shown that boiler and condenser have higher exergy destruction value of 201.37 and 33 MW, respectively. The study of the effect of feed-water heaters shows that increase in number of heaters up to 3 causes increase in both first and second low efficiency, but further increase has the reverse effect. Pressure increase in the main-steam line and the condenser causes increase and decrease in second low efficiency, respectively. The increase in re-heat temperature causes increase in out-put power and exergy destruction in boiler, turbine, and condenser. Similar results are obtained for main-steam temperature changes.

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