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PERFORMANCE ASSESSMENT OF HEAT RECOVERY STEAM GENERATOR AT DISTRICT COOLING PLANT

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ABSTRACT

Heat Recovery Steam Generators are important components in cogeneration plants. The steam produced by the Heat Recovery Steam Generator is used to produce chilled water at a District Cooling plant. The performance of the Heat Recovery Steam Generator will affect the performance of the overall District Cooling plant. This study presents the performance of the Heat Recovery Steam Generator which is based on the first and second laws of the thermodynamic principle. The following parameters, energy efficiency, exergy efficiency, exergy of fuel, exergy of product and exergy destruction of the Heat Recovery Steam Generator were analysed. The results showed that as the mass flow rate of fuel increased, the energy and exergy efficiencies of the Heat Recovery Steam Generator increased. From the results of the exergy analysis, the exergy destruction indicated the presence of the inefficiencies of the Heat Recovery Steam Generator. In order to obtain a higher performance of the Heat Recovery Steam Generator, the value of the exergy destruction must be lower.

Keywords: exergy, heat recovery, steam generator, assessment, performance.

INTRODUCTION

The Heat Recovery Steam Generator (HRSG) plays an important role in the cogeneration plant. The HRSG is used to generate steam which in turn is used to generate chilled water using the Steam Absorption Chiller (SAC).

There are many factors that affect the performance of the HRSG. OngIro *et al.* [1] noted that the mass flow rate of exhaust gas and steam, temperature of exhaust gas and steam, pressure and compositions of gas and water used in the HRSG, the geometry of the HRSG and the Gas Turbine (GT) conditions were the factors affecting the performance of the HRSG.

The performance of the HRSG can be measured through the energy and exergy efficiencies. Energy efficiency is based on the first law of thermodynamics while exergy efficiency is based on the second law of thermodynamics. There are published articles of literature based on the first law of thermodynamics reporting on the performance of the HRSG [2]. However, in the analysis where the first law was applied, account of energy degradation was not taken into account. It was found that a better approach was to apply exergy in the analysis. Exergy analysis could be used to identify the true location, magnitude and source of the inefficiency of the system [3]. Meliha Callak *et al.* [4] assessed the avoidable and unavoidable exergy destructions of a fluidized bed coal combustor and a HRSG using the exergy analysis method. The findings showed that the exergy efficiency value of the HRSG is 0.462% with exergy of fuel and product 1523kW and 704kW respectively. Butcher and Reddy [5]investigated the performance of the HRSG based on the second law of thermodynamics in an analysis using the pinch point approach. The results proved that by using the second law of thermodynamics, the details of the actual performance could be determined.

Exergy analysis related to the cogeneration plant was conducted by[6, 7]. Meanwhile, Hongwei Li and Send Svendsen [8] carried out energy and exergy analyses of the low temperature on a district heating network. An exergy analysis of the performance of the HRSG in an iron and steel factory was conducted by Mert *et al.* [9].The analysis was to determine the quality of the energy and exergy efficiencies of the thermal system. The results indicated that the energy efficiency of the HRSG is lower than its exergy efficiency. The results were also supported by [2, 4, 5].

In terms of the study on the exergy analysis related to the HRSG driven by the GT, not much published literature reported on the effect of the mass flow rate of fuel on the energy and exergy efficiencies of the HRSG. The objective of this study was to investigate the energy and exergy efficiencies of a HRSG based on the District Cooling (DC) system, using the first and second laws of thermodynamics for various mass flow rates of fuel used by the GT. The exergy of fuel, exergy of product and exergy destruction of the HRSG were also evaluated.

METHODOLOGY

In this study, a HRSG with an economizer and an evaporator was selected. First, the steam generated in the HRSG was expanded in a SAC for the generation of chilled water. Figure-1 shows a schematic representation of the DC system with the HRSG and its details.

The exhaust gas from the GT which first enters the evaporator then flows through the economizer and

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finally is discharged to the environment. Water which enters the economizer is changed into saturated steam in the evaporator, after which the saturated steam is delivered to the SAC.

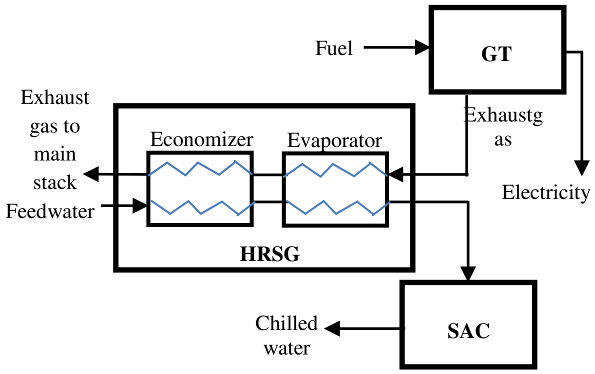

Figure-1. The HRSG based on the DC plant concept.

Thermodynamic analysis

In order to determine the energy and exergy efficiencies of the HRSG, the first and second laws of thermodynamics principles were applied.

Energy efficiency

Energy efficiency of the HRSG is defined as the ratio of energy produced by steam to the heat input. These parameters provide a measure of how the energy of heat input is efficiently converted to produce steam. Equation (1) is used to determine the energy efficiency of the HRSG [10]:

$$\eta_{HRSG} = \frac{\text{Energy produced by steam}}{(\text{gas flow } \times \text{inlet enthalpy}) + \text{fuel input on LHV basis}} \quad (1)$$

Equation (1) is simplified as:

$$\eta_{HRSG} = \frac{\dot{m}_{steam}(h_{steam} - h_{w@Tw1})}{\left(\dot{m}_{exhaust\ gas}Cp_g(T_{g1} - T_{g3})\right) + (\dot{m}_{fuel} \times LHV)} \quad (2)$$

where $\dot{m}_{steam}$ is the mass flow rate of steam (kg/s), h_{steam},the enthalpy of steam, $h_{w@Tw1}$,the enthalpy of water, $\dot{m}_{exhaust\ gas}$,the mass flow rate of exhaust gas which enters the HRSG, Cp_g,the specific heat of exhaust gas, T_{g1},the exhaust gas temperature which enters the HRSG, T_{g3}, the exhaust gas temperature leaving the HRSG, $\dot{m}_{fuel}$,the mass flow rate of fuel entering the GT (kg/s) and LHV , the Low Heating Value of the GT fuel. The $Cp_g$is calculated as[11];

$$Cp_g = 0.991615 + (6.99703 \times 10^{-5} \times T) + (2.7129 \times 10^{-7} \times T^2) - (1.22442 \times 10^{-10} \times T^3) \quad (3)$$

Exergy efficiency

The total exergy of a system consists of kinetic, potential, physical and chemical exergy respectively. In this study, the kinetic, potential and chemical exergy were negligible. Thus, the physical exergy is defined as [12]:

$$\dot{E}_n = (h - h_0) - T_0(s - s_0) \quad (4)$$

where n is represented by number of streams in the system.

The energy efficiency is a measurement of the amount of energy transferred between the exhaust gas and steam while the exergy efficiency represents the effectiveness of the quality of the energy transferred. The exergy balance is formulated as follows [13]:

$$\dot{E}_F = \dot{E}_P + \dot{E}_L + \dot{E}_D \quad (5)$$

where F, P, L and D indices are for fuel, product, loss and destruction respectively. The exergy of fuel is exergy entering the HRSG and the exergy of product is the exergy released in the form of steam. Exergy loss is thermodynamics loss caused by exergy transfer to the environment and exergy destruction is the loss due to the irreversibility within the system boundaries [9]. However, when the boundaries are drawn at ambient temperature, the exergy loss is zero.

Exergy efficiency is defined as the ratio of the exergy of product to the exergy of fuel [14];

$$\varepsilon_{HRSG} = \frac{\dot{E}_P}{\dot{E}_F} \quad (6)$$

Table-1 shows the exergy balance, exergy destruction and exergy efficiency of the HRSG.

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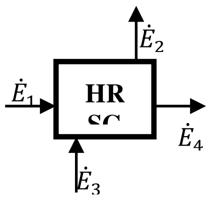
Table-1. The exergy balance, exergy destruction and exergy efficiency of the HRSG.

	Stream no.	Identification
	1	Exhaust gas
	2	Exhaust gas
	3	Water
	4	Steam
	$\dot{E}_F = \dot{E}_1 - \dot{E}_2$ $\dot{E}_P = \dot{E}_4 - \dot{E}_3$ $\dot{E}_D = (\dot{E}_1 + \dot{E}_3) - (\dot{E}_2 + \dot{E}_4)$ $\varepsilon_{HRSG} = \frac{(\dot{E}_4 - \dot{E}_3)}{(\dot{E}_1 - \dot{E}_2)}$	

Case study

The DC plant at Universiti Teknologi Petronas (UTP) located in Perak, Malaysia was taken as a case study. The plant operated from 7 a.m. to 11 p.m. on weekdays and 7 a.m to 3 p.m. on weekends. The HRSG capacity is 12 tons/hr. The following assumptions were used for the analysis [5]:

(i) System was in a steady state.
(ii) Fuel used was Methane.
(iii) No pressure drop at steam side.
(iv) Pressure drop on gas side did not affect its temperature.
(v) Pinch and approach points were negligible.
(vi) Steam temperature was 180°C.

RESULTS AND DISCUSSIONS

The effect of the mass flow rate of fuel used by GT on energy and exergy efficiencies of the HRSG is presented in Figure-2. The results indicate that as the mass flow rate of fuel increased, the energy efficiency of the HRSG increased. However, the exergy efficiency curve peaks at 0.22 kg/s of the mass flow rate of fuel, after which it shows a gradual dip.

Therefore it can be seen that the exergy efficiency of the HRSG was higher than its energy efficiency. For a given mass flow rate of fuel, the energy efficiency of the HRSG reached 30% while the exergy efficiency peaked at 70%. These results show that the quality of energy in terms of the percentage that was transformed to steam was higher than the amount of energy converted to steam.

Unlike energy efficiency, the exergy efficiency trends show a fluctuation that indicates the actual percentage of the fuel exergy provided to a system. It is important to determine exergy efficiency in order to assess the thermodynamics of the performance of the HRSG relative to the present-day performance level of the HRSG [14]. The following two factors that influenced actual exergy efficiency were the operating condition of the HRSG and the temperature of the exhaust gas entering the HRSG.

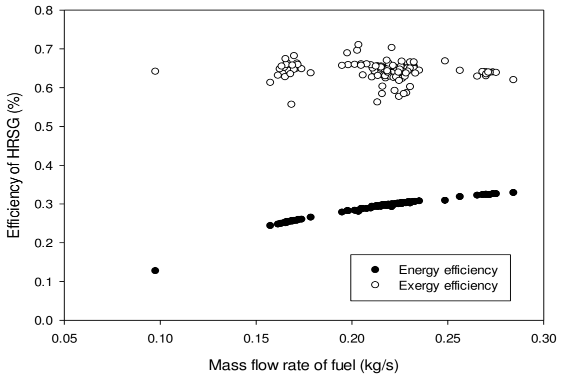


Figure-2. Variations in efficiencies with the mass flow rate of fuel.

In the case study of the HRSG, an illustration of the exergy analysis is shown in Figure-3. The exergy of fuel represents the resources that are expanded to generate the steam as a product, while the exergy of product is the desired output produced by the HRSG. The average exergy of fuel is 1.4 MW and the exergy of product is 0.9 MW. The fuel exergy wasted represents exergy destruction which is 0.5MW.In addition; exergy destruction is indicated by a measurement of the inefficiencies of the HRSG.

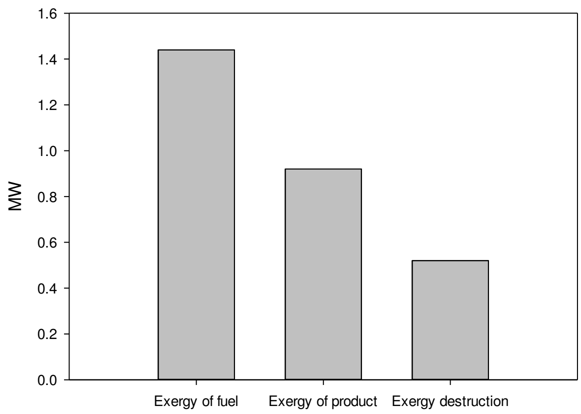


Figure-3. Comparison of exergy fuel, product and destruction of the HRSG.

A summary of the results for the energy and exergy analyses is tabulated in Table-2. The results obtained are used to make a comparison with the results of the other components, the GT and the SAC of the DC plant, which are also useful for a maintenance schedule.

Table-2. Summarized results of the energy and exergy analyses of the HRSG.

η_{HRSG}	**0.30%**
ε_{HRSG}	0.64%
$\dot{E}_F$	1.44 MW
$\dot{E}_P$	0.92 MW
$\dot{E}_D$	0.52 MW

CONCLUSIONS

In this study, the first and second laws of thermodynamics were applied to the HRSG in the DC plant. The actual operation data were used to obtain the energy and exergy analyses results. In the case of a HRSG with 12 tons/hr capacity, the average exergy of fuel, the exergy of product and the exergy destruction were 1.44 MW, 0.92 MW and 0.52 MW respectively. The energy and exergy efficiencies showed that the percentage of the fuel exergy in produced steam was higher than the energy of fuel converted to steam. Thus, this proves that exergy analysis can be used as a tool not only to determine the actual performance of the HRSG but also to investigate the performance of the overall DC plant.

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